UNIVERSITY OF ALBERTA

ELEMENTS OF A GENETIC FRAMEWORK FOR INCLINED HETEROLITHIC STRATA OF THE McMURRAY FORMATION, NORTHEAST ALBERTA

BY

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Canada

"Between two evils, I always pick the one I never tried before."
- Mae West

"The closed mouth gathers no feet."
- Chinese proverb

Facts are simple and facts are straight
Facts are lazy and facts are late
Facts all come with points of view
Facts don't do what I want them to
Facts just twist the truth around
Facts are living turned inside out
Facts are getting the best of them
Facts are nothing on the face of things
Facts don't stain the furniture
Facts go out and slam the door
Facts are written all over you face
Facts continue to change their shape
- from Crosseyed and Painless by the Talking Heads

"Your friend is the man who knows all about you, and still likes you."
- Elbert Hubbard

This thesis is dedicated the hours of 10 pm to 4 am, without which none of this would have been possible.

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CHAPTER 1 - INTRODUCTION

Lower Cretaceous strata in western Canada host several major unconventional petroleum deposits. These include the Athabasca, Peace River, and Cold Lake Oil Sands, and the Lloydminster district heavy oil deposit (Fig. 1.1). The Athabasca Oil Sands comprise the largest of these deposits, with in place bitumen reserves estimated at 1.3 trillion barrels (ERCB, 1990). Most of the Athabasca deposit (894 x 10^9 bbl) is contained within loosely consolidated deposits of the McMurray Formation and within the overlying Wabiskaw Member of the Albian Clearwater Formation.

Production from the Athabasca deposit has been building since commercial development first began in the late 1960's, and currently accounts for 31% of Canada's oil production (C.A.P.P. website). Numerous new surface and subsurface oil sands projects are in development and, as in situ techniques of bitumen recovery become more refined, development of this resource will flourish.

The McMurray Formation is stratigraphically complex, consisting primarily of sandy and heterolithic siliciclastics within an inadequately understood genetic framework. The Formation has been informally divided into lower, middle and upper units (Carrigy, 1959) reflecting dominantly continental, estuarine and shoreline deposition, repectively (Ranger and Gingras, 2003).

Within the estuarine middle McMurray, inclined heterolithic strata (IHS) comprise a major facies, and are commonly found in association with sand-rich facies targeted as highly productive bitumen reservoirs. The IHS deposits are sedimentologically complex, and a proper understanding of their genetic aspects has been elusive.

Carrigy (1971) interpreted IHS within the McMurray Formation as foreset deposits of small, Gilbert-type deltas prograding northward into a standing lacustrine or lagoonal body. Mossop and Flach (1983) proposed deposition through the action of deep (20 – 45 m) meandering fluvial channels. An estuarine channel interpretation was introduced by Stewart and MacCallum (1978), and later supported by the ichnological

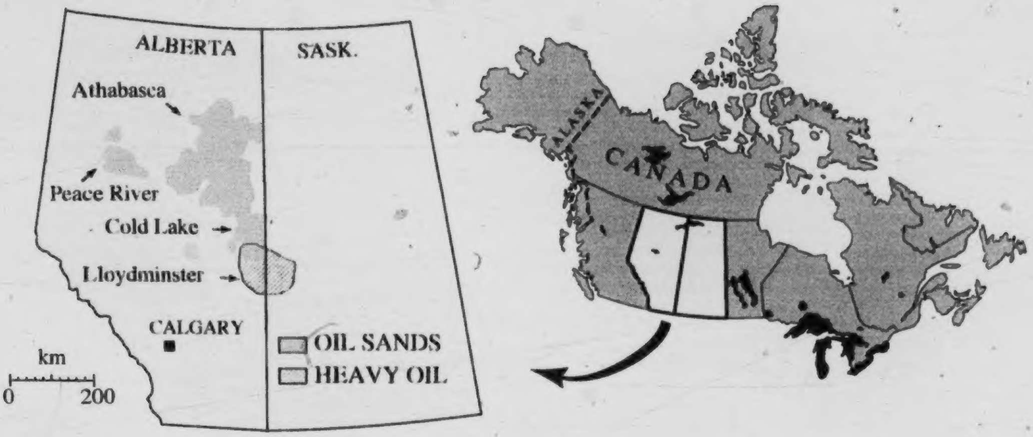

Figure 1.1. Oil sand and heavy oil deposits of western Canada. From Ranger and Gingras (2003).

work of Pemberton et al. (1982), and comparative work in modern settings by Smith (1987, 1988a, 1988b). Subsequently, a number of studies have built upon the estuarine interpretation of middle McMurray sedimentation (e.g. Fox, 1988; Ranger and Pemberton, 1992; Bechtel et al., 1994; Ranger, 1994; Yuill, 1995; Bechtel, 1996; Ranger and Pemberton, 1997; Wightman and Pemberton, 1997; Harris, 2003).

While IHS deposits of the McMurray Formation have received cursory attention in many studies, little has been done to characterize their fine scale aspects and classify the variation exhibited between occurrences. The application of a "mud-dominated" versus "sand-dominated" classification has been used by many studying the McMurray Formation. Deposit character, however, exhibits far more complexity and variation than can be accommodated in such a rudimentary scheme. Some researchers have attempted to refine the basic estuarine channel depositional model, introducing depositional characteristics identified through the investigation of modern estuarine systems (e.g. Ranger and Pemberton, 1992; Bechtel et al., 1994). In these studies, contrasting position along a riverine estuary has been suggested as the impetus behind the variable lithic character of the IHS, with the heterolithic nature of the sediment being attributed to temporal shifts in the locus of suspension deposition.

In order to advance understanding of the McMurray Formation's genetic and

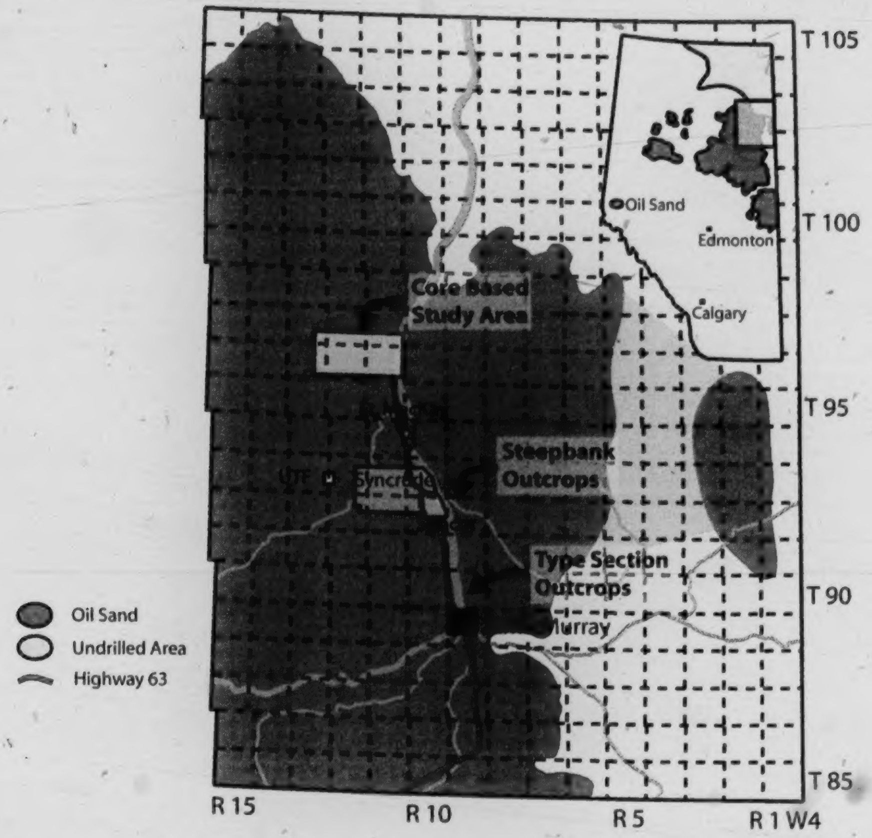

Figure 1.2. Location of cored area and outcrops featured prominently in this study. Modified from Wightman and Pemberton (1997).

stratigraphic aspects, a more thorough treatment of the IHS is needed. A detailed understanding of these deposits is of particular importance for in situ development, as heterogeneous elements play a key role in the proper modeling and gainful exploitation of subsurface reservoirs.

This study was undertaken to characterize and classify IHS within the McMurray Formation, and insomuch as is feasible, interpret the depositional controls of sediment character. The bulk of information gathered came from the subsurface, using drill cores from the Horizon Project oil sands lease of Canadian Natural Resources Limited (Fig. 1.2). Several additional cores from outside of this area were examined to help characterize a distinctive bioturbate texture encountered during the course of the study. In all, intervals of twenty-eight well cores were examined, representing approximately 900 m of logged section. To supplement core work, numerous outcrops along Sappree Creek, and the Athabasca, Hangingstone, Horse, McKay and Steepbank Rivers were visited, although no regimented campaign of fieldwork was undertaken.

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CHAPTER 2 - INCLINED HETEROLITHIC STRATA OF THE LOWER CRETACEOUS McMURRAY FORMATION, NORTHEASTERN ALBERTA – AN EXAMPLE OF SEDIMENTOLOGIC AND ICHNOLOGIC VARIATION ALONG AN ANCIENT RIVERINE ESTUARY

INTRODUCTION

THE McMURRAY FORMATION

The Athabasca Oil Sand deposit of northeast Alberta (Fig. 2.1) is truly one of Canada's greatest natural resources. With estimated in place bitumen reserves of approximately 900 billion barrels (Wightman and Pemberton, 1997), it is possibly the largest single accumulation of hydrocarbons in the world. Development has historically been hampered by engineering problems related to the high weight and viscosity of the oil (Carrigy, 1971). Both the private and public sectors have sponsored considerable research to overcome many of the developmental challenges associated with the deposit. Commercial exploitation has been building since the late 1960's. Production of 273 000 barrels from the deposit accounted for 16% of the nation's total oil production in 1995, and is expected to rise considerably through the foreseeable future (Wightman and Pemberton, 1997).

Within the deposit, the Lower Cretaceous (Aptian and older) (Stelck and Kramers, 1980) siliciclastic McMurray Formation forms the most volumetrically significant portion of the reservoir. Owing to relatively shallow burial (not more than 500' greater than present) (Nelson and Glaister, 1978), the McMurray Formation has undergone little diagenetic alteration. Accordingly, reservoir character is largely dictated by primary sediment character (Mossop and Flach, 1983), and an understanding of the depositional framework of the McMurray Formation is key to its gainful exploitation.

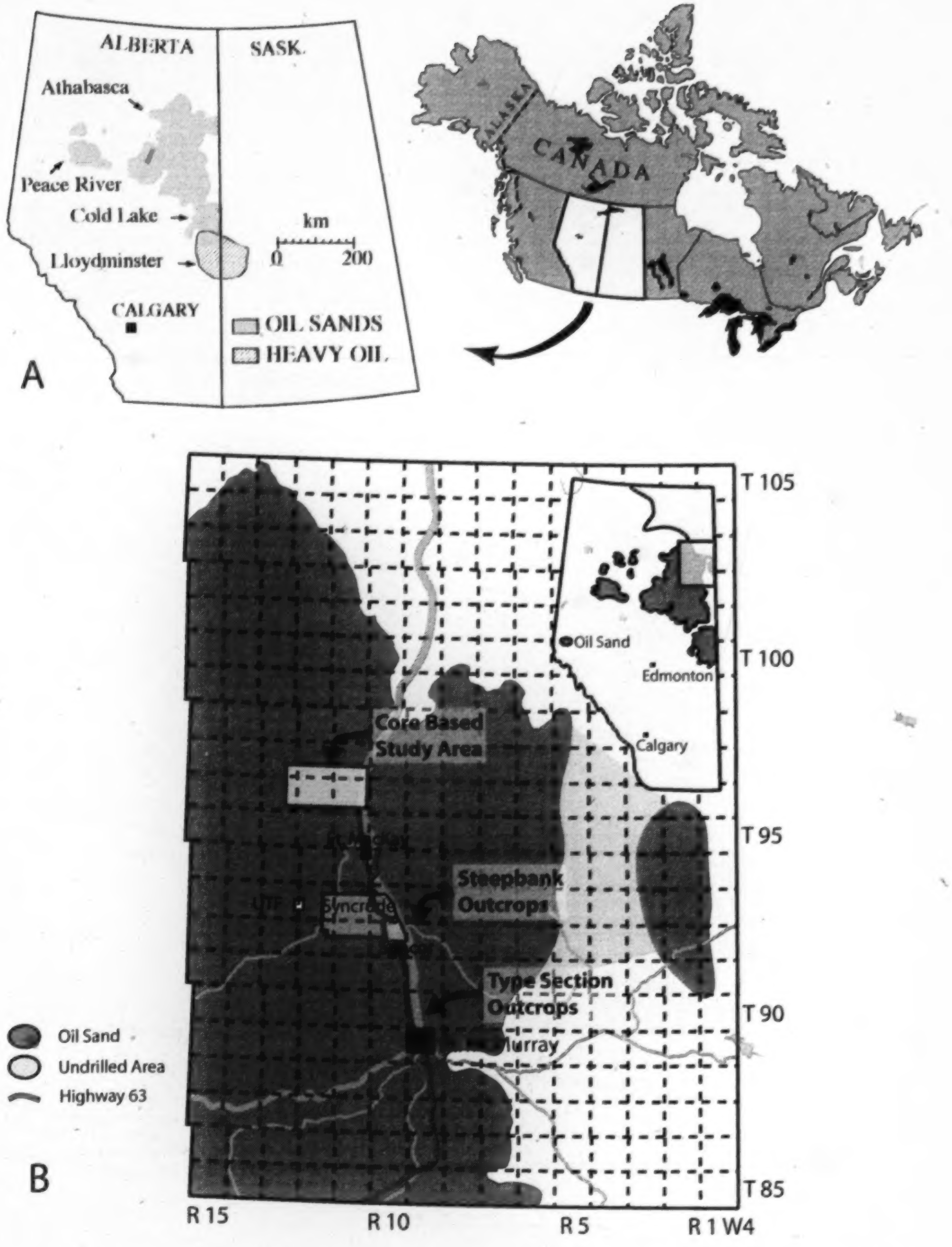


Figure 2.1. Location of the study area. **(A)** The Athabasca Oil Sand deposit is located in northeast Alberta, and is one to three such deposits in the province. From Ranger and Gingras (2003). **(B)** This study focuses on core retrieved from Canadian Natural Resource Limited's Oil Sand development lease in Townships 96 & 97, Ranges 11 – 13 W4. Additional data has been gained through examination of outcrop along the Steepbank and Athabasca Rivers. Modified from Wightman and Pemberton (1997).

The McMurray Formation is riddled with stratigraphic complexity; while extensively drilled, and locally exceeding 100 m in thickness, no formal internal division has been developed. Indeed, facies correlation over distances of as little as several hundred metres can be challenging. Most of the resource must be developed using in situ production techniques, as only approximately 10% of the deposit can be accessed through surface mining (Wightman and Pemberton, 1997; Ranger and Gingras, 2003). In comparison with surface development, in situ production requires a more detailed understanding of reservoir elements, their spatial and genetic relationships, and their behavior under production conditions.

The McMurray Formation comprises the basal portion of the Lower Cretaceous Mannville Group in northeastern Alberta. It lies directly on Devonian carbonates, which subcrop along the sub-Cretaceous unconformity surface (Fig. 2.2). Prior to deposition of the McMurray Formation, the exposed carbonate terrane was subject to differential erosion, which created a broad valley known as the McMurray subbasin (Fig. 2.3). This broad trough was bounded to the east by the Precambrian Shield and to the west by resistant reefal carbonates of the Grosmont Formation (Stewart and MacCallum, 1978). The generation of the McMurray Subbasin was greatly influenced through the solution removal of Elk Point Group evaporites, and structural collapse of the overlying Beaverhill Lake Group. Salt solution and structural collapse continued through the deposition of the McMurray Formation, and are thought to remain active today.

Through the Aptian and Albian, the pulsed transgression of the Boreal Sea (Ranger and Pemberton, 1997) led to the filling and eventual overtopping of the McMurray paleo-valley with clastic sediments of the McMurray and Clearwater Formations. The McMurray Formation has been informally divided into lower, middle and upper members (Carrigy, 1959), loosely reflecting continental, estuarine and shoreline depositional environments respectively (Ranger and Gingras, 2003). Sediment was fed to the McMurray Subbasin through a major continental drainage system

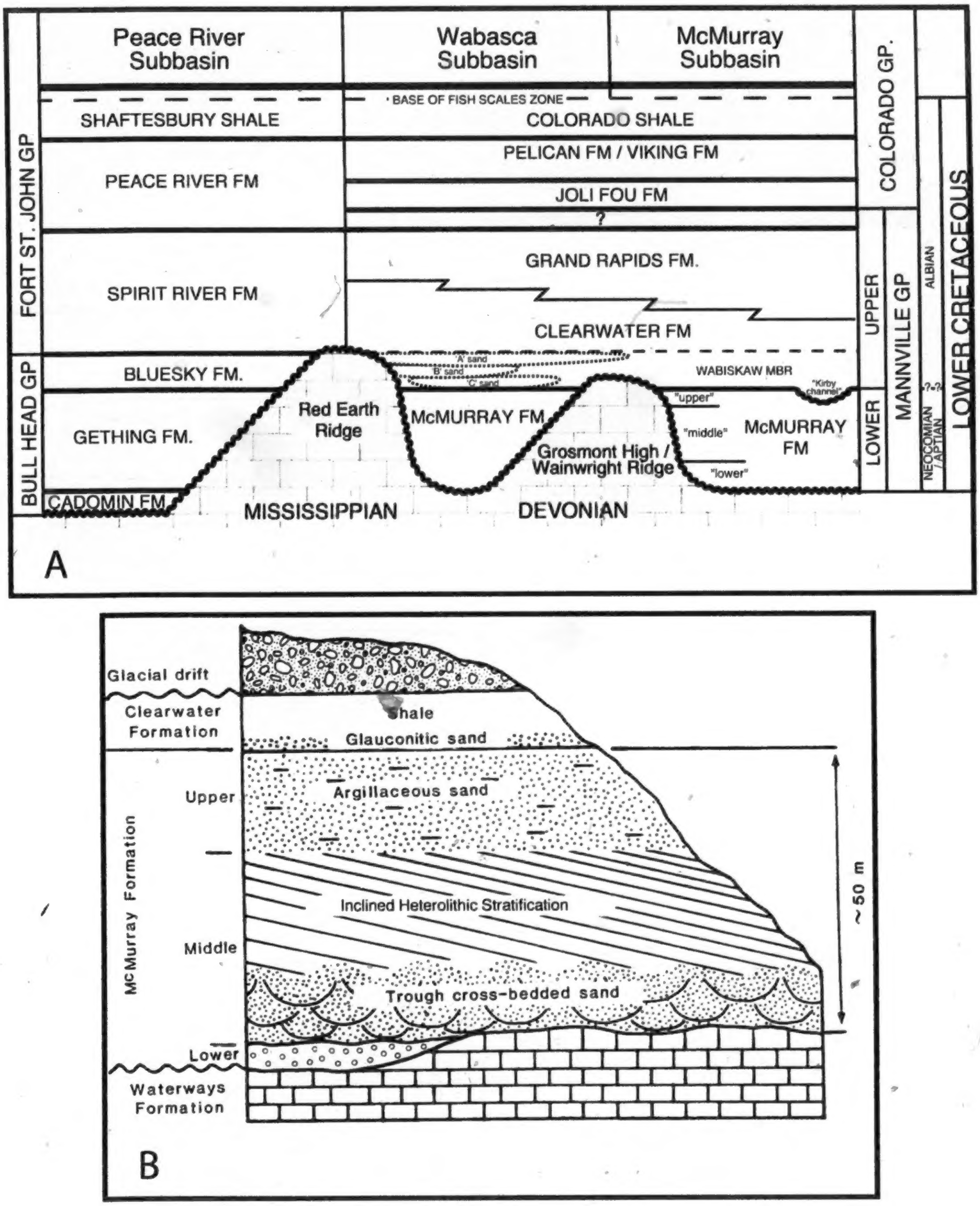


Figure 2.2. Stratigraphic framework of the McMurray Formation. **(A)** Stratigraphy of the Lower Cretaceous within north-central Alberta. From Ranger and Gingras (2003). **(B)** Informal stratigraphic subdivision within the McMurray Formation, and associated lithic character. From Mossop and Flach (1983).

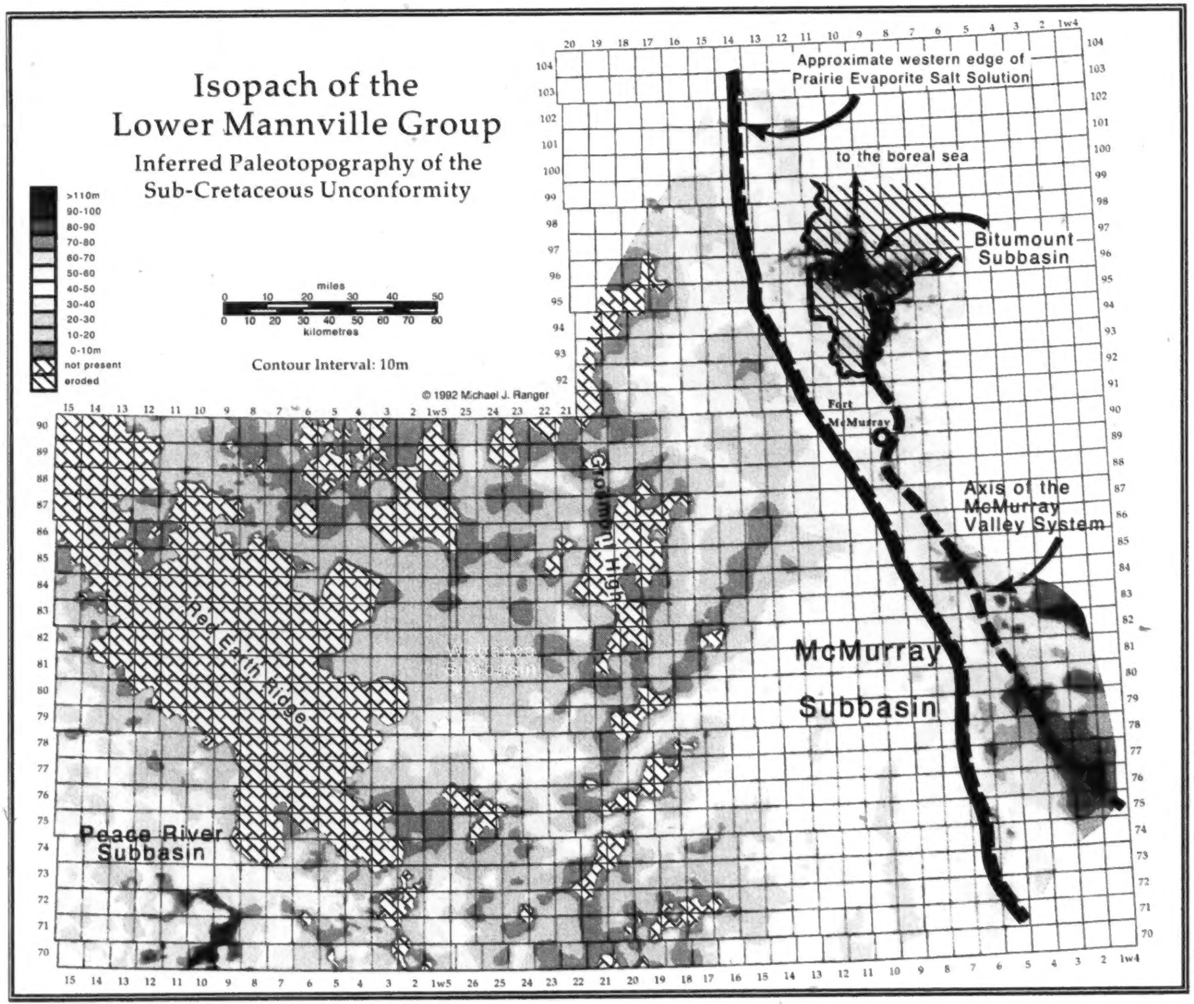


Figure 2.3. Inferred paleotopography of the sub-Cretaceous unconformity surface, as expressed by the thickness of the McMurray Formation and its stratigraphic equivalents. Note the presence of several subbasins, separated by highlands of resistant carbonates. Courtesy of Michael Ranger.

entering from the southeast, as well as regional drainage systems shedding off the carbonate highlands to the west and the Precambrian shield to the east. Deposition of the marginal marine McMurray Formation continued while the ridges of resistant carbonate limited Mannville Group deposition to several isolated subbasins. As these highs were overtopped, subareally exposed source areas were lost and less restricted marine circulation came into effect. Deposition of the McMurray Formation was then superceded by glauconitic shoreface sandstone and basinal mudstone of the Clearwater Formation.

INCLINED HETEROLITHIC STRATA

The term Inclined Heterolithic Stratification (IHS) was introduced by Thomas et al. (1987) as a descriptor for heterogeneous deposits which exhibit notable primary dip. Prior to this, numerous clumsy, often genetically suggestive terms had been applied to such deposits (e.g. epsilon cross-stratification, lateral accretion bedding). While "the overwhelming majority are the products of point bar lateral accretion within meandering channels" (Thomas et al., 1987), IHS may also be generated through progradation of Gilbert-type deltas and suspension fall-out onto existing slopes. Along with the term IHS came a system of nomenclature for describing the features internal to an IHS set, and the relationships between sets (Fig. 2.4).

IHS deposits have been examined in of both modern depositional environments (e.g. Smith, 1988a; de Mobray, 1983) and the rock record (e.g. Rahmani, 1988; Wood; 1989; Eberth, 1996; Lavigne, 1999). Most examples have been attributed to point bar accretion from tidally influenced channels.

Within the McMurray Formation, IHS forms a major component of the estuarine middle member, occurring in successions locally exceeding 40 m in thickness. Such successions may be composed wholly of IHS, or may contain both IHS and an underlying, loosely associated facies of clean, megaripple bedded sand. The IHS itself is typically composed of interbedded sand and mud in varying proportions, exhibiting primary dips of 2° - 20°.

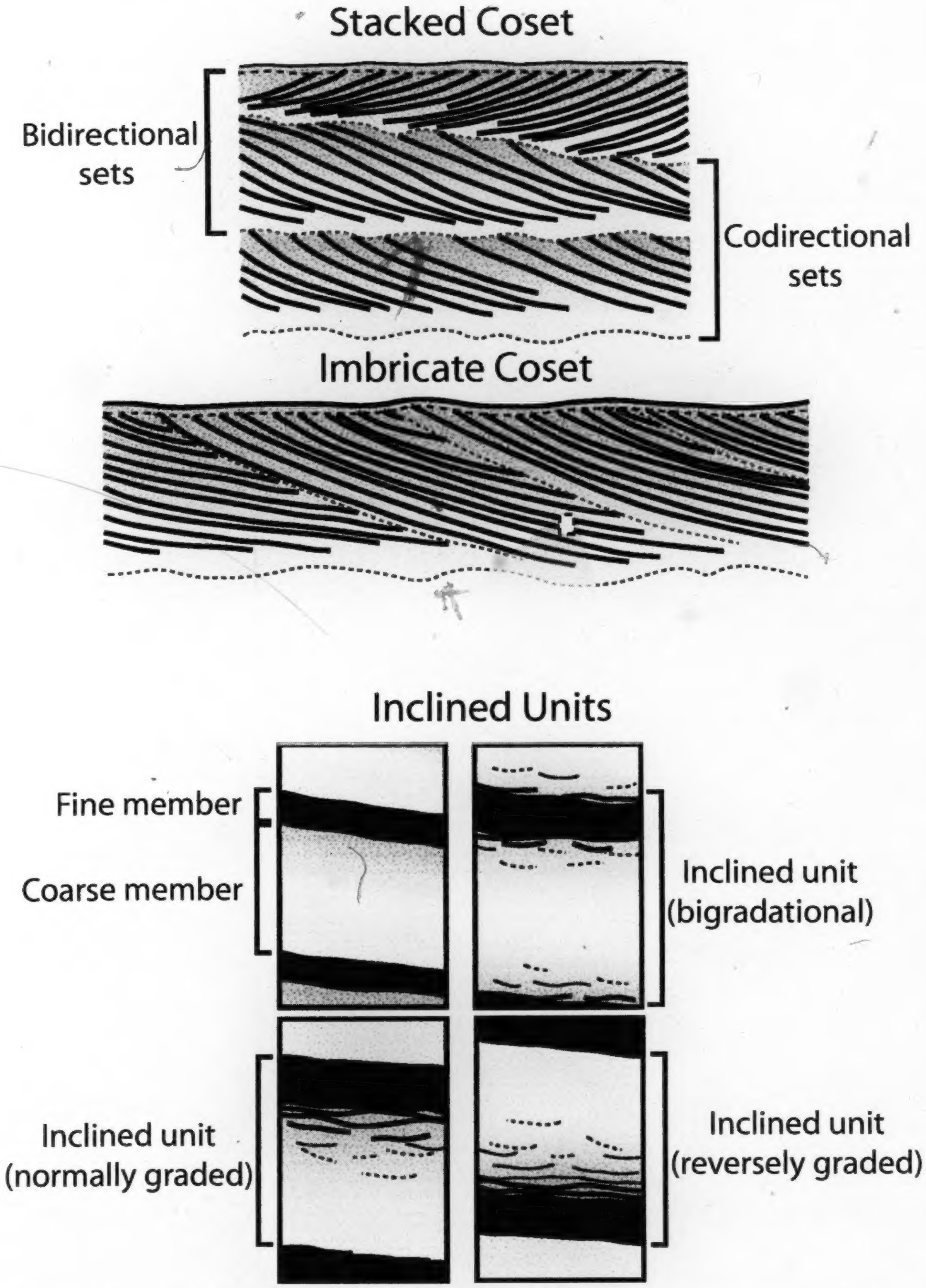


Figure 2.4. Nomenclature used in the description of IHS sets, their constituents, and their relationship. Modified after Thomas et al. (1987).

Carrigy (1971) presented the first notable work concerning the genesis of McMurray Formation IHS. It was his opinion that the IHS successions had formed as the foresets of Gilbert-type deltas prograding into a lacustrine or lagoonal setting. This interpretation did not, however, stand up to detailed outcrop examination.

Working individually and collaboratively, Mossop and Flach (Mossop, 1980; Mossop and Flach, 1983; Flach and Mossop, 1985) developed a coastal plain interpretation for McMurray Formation deposition. This model linked rising sea level in the Boreal Sea (encroaching from the north) to a change in fluvial depositional character from moderately deep, coarse-grained, braided channels to deep (20 – 45 m), fine-grained, meandering channels.

Largely through outcrop examination, they identified several key features supporting a channel mode of deposition. Among these features were: a scoured base to the megarippled sands, an overall fining- and muddying-upwards profile through the successions, paleoflow perpendicular to the dip in the IHS, and continuity of bedding through the transition between the IHS sets and the underlying sands. The megaripple bedded sands were taken to be the deposits of large-scale bedforms migrating on the channel bed, while the overlying IHS reflected the lateral accretion of a contemporaneous point bar. Within the IHS sets, the coarse member sand beds were believed to have formed under fluvial flood conditions, and the fine member silty partings under intervening low flow conditions. While the scale of the depositional channels and continuity of bedding between the IHS packages and underlying sands, and indeed within the IHS packages themselves, remain contentious issues (Ranger and Gingras, 2003), the reasoning of Mossop and Flach represented a major step forward.

Mossop (1980) noted that 'meander belts' of these middle McMurray channels are amongst the thickest and richest pay zones encountered in the Athabasca deposit. The basal megarippled facies is composed of clean, moderately well-sorted sands, as are the coarse members within the IHS, albeit with reduced grade due to the presence of the silty partings.

The first researchers to assert an estuarine interpretation for the bulk of McMurray Formation deposition were Stewart and MacCallum (1978). Although thin on evidence, their field guide presented many ideas that are still considered valid today. Within an overall trangressive system, they indicated that repeated fluctuation of sea level drove conditions to vary between fluvial and estuarine, with IHS deposition taking place on the accretionary banks of estuarine channels. Stewart and MacCallum (1978) proposed that the bulk of the mature sand contained within the McMurray Formation was sourced from the Proterozoic Athabasca sandstone of the Precambrian Shield and Jurassic sands to the south.

Several studies have since built a solid case for a tidally influenced, brackish channel depositional model for the middle McMurray IHS complexes. These studies have focused on sedimentological and ichnological lines of evidence (e.g. Pemberton et al, 1982; Smith, 1988b; Ranger and Pemberton, 1992; Bechtel et al., 1994), as well as on the identification of modern estuarine channels depositing analogous packages of sediment (Smith, 1987; 1988a). Core based study of McMurray Formation IHS successions has demonstrated a greater variation in IHS depositional character than is readily observed in outcrop (e.g. Bechtel et al, 1994). IHS packages vary in style from those dominated by clean sand beds, to those composed almost exclusively of silty mud. Similarly, variation is seen in the abundance and nature of biogenic structure within the sediment. This variation has been attributed to contrasting positions within a channelized estuarine system, which would lead to differing influence of saltwater intrusion and suspended load deposition (Ranger and Pemberton, 1992). The heterogeneous character within the IHS has been attributed to spatial shifts in the freshwater-saltwater interface and associated highly turbid water (Bechtel et al., 1994). The temporal scale of these shifts has not, however, been clearly demonstrated.

THE ESTUARINE ENVIRONMENT

Dalrymple et al. (1992) define an estuary as: *the seaward portion of a drowned valley system which receives sediment from both fluvial and marine sources and which contains facies influenced by tide, wave and fluvial processes.* Frey and Howard (1986) define an estuarine sequence as: *a complex of intertidal and shallow subtidal, mostly channel-form intracoastal facies dominated to some extent by tidal processes, exhibiting conspicuous variations in sediment texture, composition, and provenance, and in physical and biogenic sedimentary structures.*

From the first definition, it is apparent that estuaries are generated during transgression, when the creation of accommodation space outpaces the influx of continentally derived sediment, and thus are geologically ephemeral features. An estuary acts as a depositional sink, fixing sediment sourced from both fluvial and marine ends of the system. Estuaries have high depositional budgets influenced through two broad processes: water circulation patterns that promote the transport of sediment from both ends of the system towards a central area of minimal energy, and the conversion of fluvial suspended load into aggregates.

From the second definition, it is apparent that estuarine deposits contain great internal variation of character, reflecting variation in sediment input and depositional processes within estuarine systems. The deposits of estuaries may appear chaotic at first glance. If deposit character can be systematically assigned to subenvironments within an estuary, however, a clear spatio-temporal framework for deposition may be resolvable.

PHYSICAL ASPECTS OF THE ESTUARINE ENVIRONMENT

Water Circulation

Estuarine water circulation patterns have traditionally been divided into three classes based on the degree of interaction between fresh and saline water. Circulation within estuaries is driven by a combination of fluvial inflow, tidal forcing, wind generated turbulence and density contrasts related to differing salinity. The basics of classification are presented here, for a more in-depth treatment, the reader is directed to Dyer (1986).

In the first circulation type, a salt wedge estuary (Fig. 2.5A), little hydraulic forcing is exerted from the marine end of the system (i.e. minimal tidal flow). As a result, fresh water introduced from the fluvial source flows overtop of a relatively stable wedge of higher density saline water, with little mixing taking place between the two bodies. In this type of system, flow within the estuary is dominated by a steadily decaying seaward current in the fresh upper layer.

The second type of estuary, termed a partially mixed estuary, is common where continental drainage and tides both exert appreciable influence (Fig. 2.5B). This appears to have been the case with systems acting during the deposition of the middle McMurray Formation. Turbulent flow associated with tidal forcing leads to the mixing of fresh and saline water along their interface. As saline water is mixed into the upper, fresher flow, and carried seaward, additional saline water must flow landward along the base of the estuary to replace it. This sets up a situation in which time-averaged, residual currents along the bottom are convergent towards the landward limit of saline water intrusion. Both density driven circulation and salinity stratification are enhanced during times of heightened fresh water influx.

In cases where tidal energy dominates over fluvial energy a well mixed estuary results (Fig. 2.5C). In this type of estuary, nearly complete vertical mixing of the water column takes place, and salinity variation is set up horizontally rather than vertically. Flood and ebb flows commonly follow separate pathways, influenced by the Coriolis effect and inherited estuary form.

Aggregation of Suspended Fines

Within estuaries, fine suspended load material introduced from continental drainage comes together to form agglomerated "grains", which are much more disposed to deposition than their constituent particles. The aggregation of fines takes place through

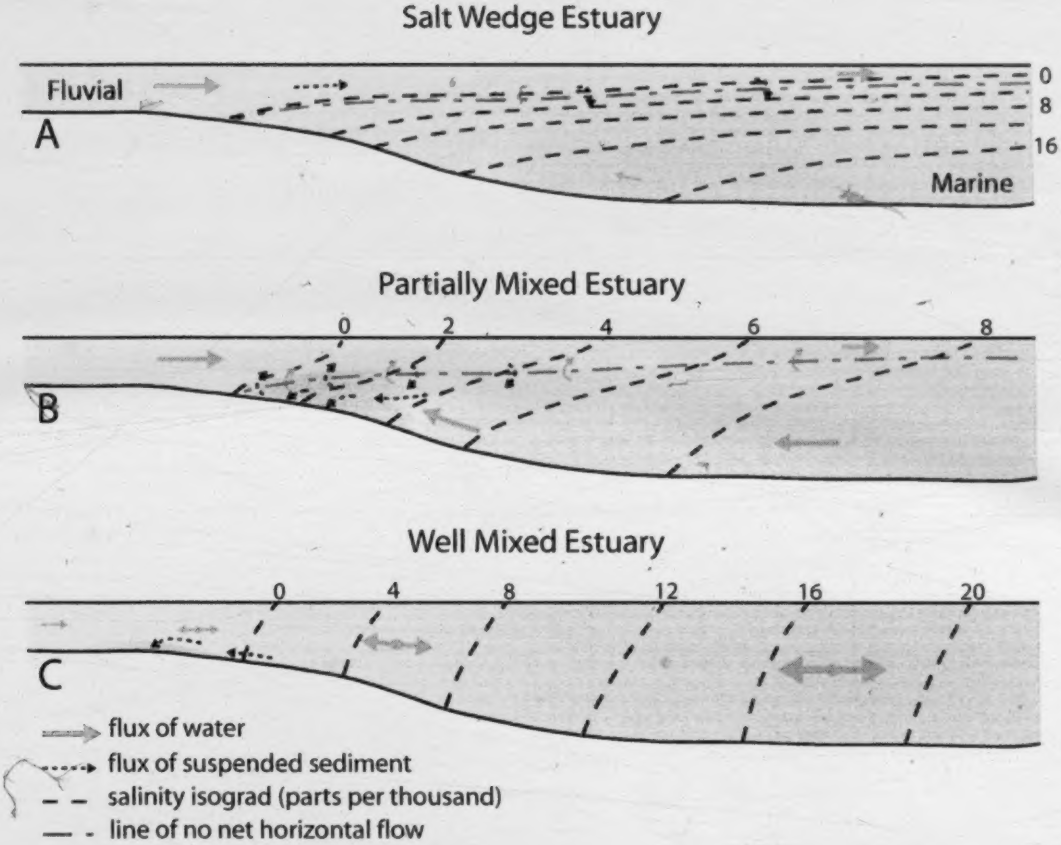


Figure 2.5. The classification of estuaries based on their patterns of internal water circulation. **(A)** Salt wedge estuaries are typical of coasts that experience minimal tidal range. **(B)** Partially mixed estuaries form where both fluvial and tidal forcing exert appreciable influence on water movement. **(C)** Well mixed circulation is typical of estuaries experiencing considerable tidal influence, but little fluvial influx.

two processes: flocculation and biogenic packaging.

Salinity flocculation occurs as a result of the interaction of clay particles and dissolved ions in saline solutions. Clay particles are rimmed by unsatisfied bonds and as a result of the coulombic force repel each other in chemically neutral media such as fresh water. When dissolved ions are introduced to the system (e.g. through mixing with saline water), cations in the solution form a buffering layer along the face of the clay particles. This suppresses the coulombic force and allows the particles to come together as a result of the attractive Van der Waals force. Suspended clay matter then assembles to form loose aggregates, known as flocs, which behave hydraulically as particles larger than their constituents. Through this process fine suspended particles can attain a critical mass and settle from the water column. Most flocculation takes place at salinities of less than 3 parts per thousand, or approximately one tenth that of seawater (Meade, 1972). For a more thorough outline of the process of salt flocculation and its controls, the reader is directed to Pryor (1975), Kranck (1981), and Dyer (1986). Flocculation also takes place as a result of the interaction of suspended fines and organic compounds (Meade, 1972), although this process is complex and its controls are poorly understood.

The agglomeration of suspended particulate material may also take place through the action of suspension feeding organisms. Both benthic and planktonic filter feeders contribute to this process through the production of feces and pseudofeces (material ejected prior to ingestion). Fecal pellets are typically densely packed, resistant to abrasion and composed dominantly of inorganic material. The size and shape of the pellets vary greatly with the type and size of producing organism. Pellets often behave hydrodynamically as sand grains in bedload transport (Pryor, 1975). The depositional significance of pellet production is variable, but is often substantial (Frey and Howard, 1986). Pryor (1975) showed that filter feeding *Callianassa* shrimp can produce pellets at rates equivalent to an annual accumulation of 0.5–14 cm, depending on the density of their colonization.

While the agglomeration of suspended fines allows suspended material to settle from the water column, deposition is often short-lived, with fluctuations in energy leading to common re-entrainment and redistribution.

Concentration and Localized Deposition of Fines

Within modern estuaries, a localized zone of highly turbid water is often present. This zone of high suspended load is referred to as the Turbidity Maximum and is common in mesotidal and macrotidal estuaries exhibiting a partially mixed character (Meade, 1972; Allen et al, 1980; Kranck, 1981; Gelfenbaum, 1983; Dyer, 1986; and

Ciffroy et al., 2003). The generation and maintenance of the turbidity maximum is facilitated through a combination tidal current asymmetry and density circulation.

When tidal forcing dominates over density driven circulation (i.e. when fluvial influx is low), fines are commonly concentrated landward of the salinity node, near the limit of tidal flow reversal due to an asymmetry of tidal flow (Postma, 1967). In the upper reaches of a tidally affected system, the dynamics of tidal flow are typically altered from sinusoidal rise and fall into an asymmetric pattern characterized by a shortened, more energetic flood tide and a longer lived, subdued ebb tide (Fig. 2.6A). This generates a situation in which total shear is greater during flood flow, resulting in greater erosion and transport of fines. In addition to the more intense flood tide, the flood slack period is longer than the ebb slack period, leading to greater deposition from suspension. The combination of these two factors leads to a time-averaged landward transport of material towards the tidal node (Fig. 2.6B).

When density circulation dominates over tidal forcing (i.e. when fluvial influx is high), fines are commonly concentrated near the salinity node, where residual bottom currents converge. As fluvially sourced suspended material enters the estuary, a combination of declining flow velocity (related to widening of the channel system) and aggregation (due to salinity flocculation and increased biologic activity) causes most of the suspended load to descend into the bottom, landward directed current, where it is carried back up the system. In the vicinity of the density node, the fines are deposited due to a combination of reduced energy and extreme suspended load concentration, or recycled back into upper, seaward flow (see Fig. 2.5B).

Temporal Variation in Depositional Dynamics

Sediment transport and deposition within an estuarine system are by no means steady processes. Indeed, variation takes place on several temporal scales, and can be readily followed by tracking the behavior of the turbidity maximum.

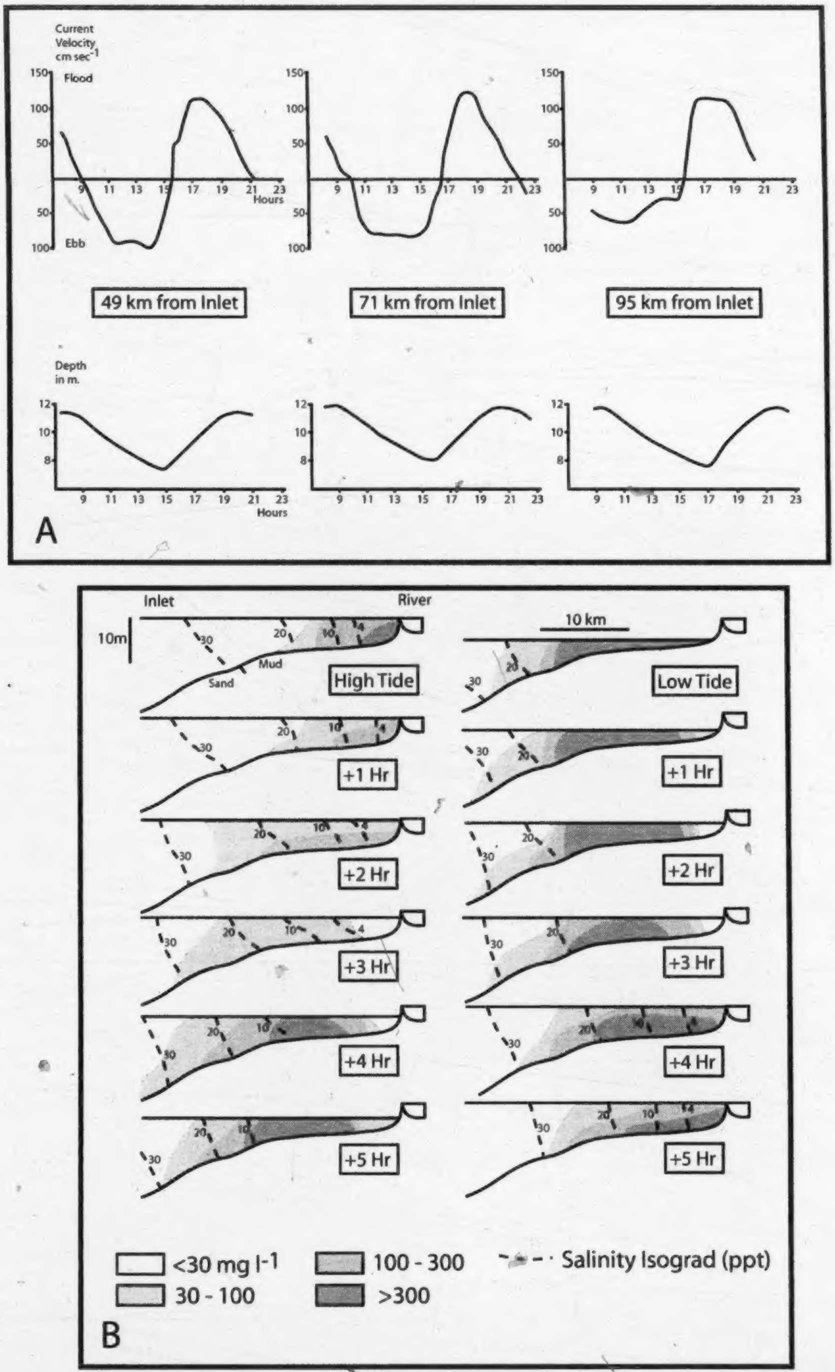


Figure 2.6. The dynamics of tidal transport in an estuarine channel. **(A)** Landward distortion of the 'tidal wave' within the Gironde estuary. This phenomenon leads to a short, intense flood tide and a longer, weaker ebb tide. From Allen et al. (1980). **(B)** The cycle of suspended load transport within the Daule River estuary. Note that a greater concentration of fines is entrained by the flood tide than the ebb tide. This leads to the time-averaged landward transport of fine-grained material. From Allen et al. (1980).

On the diurnal scale, the position and sediment load of the turbidity maximum are seen to evolve with the tidal flow cycle. Gelfenbaum (1983) showed that within the mesotidal Columbia River estuary, during periods of low fluvial inflow, the turbidity maximum made semidiurnal excursions of approximately 20 km up and down the system. In the macrotidal Aulne estuary, Allen et al. (1980) observed not only migration of the turbidity maximum, but also deposition from, and resuspension into it on a semidiurnal cycle.

On the fortnightly scale, the strength of tidal flow is seen to rise and fall. As a result, the ability of the flow to entrain and transport sediment rises and falls in concert. With respect to fines transport, spring tides are characterized by high erosional capacity, and high suspended load within the turbidity maximum. During neap tides, reduced flow strength leads to reduced erosional capacity, declining suspended load, and large scale deposition of fines. In the Gironde estuary, pools of fluid mud accumulate in lows during neap tides, only to be resuspended during the following spring tide (Allen et al., 1980). The range over which the turbidity maximum migrates during its semidiurnal excursion should also vary fortnightly as a result of changes in the volume of tidal exchange.

On the seasonal scale, the position and behavior of the turbidity maximum vary in relation to fluvial discharge and associated changes in water circulation dynamics (Allen et al., 1980; Uncles and Stephens, 1993). During low fluvial discharge, the generation and maintenance of the turbidity maximum is influenced mainly by tidal processes. This results in a diurnally migrating turbidity maximum that is found just seaward of the limit of tidal reversal (Fig. 2.7). During high fluvial discharge, density circulation drives the maintenance of the turbidity maximum. It is located in the vicinity of the density node, which has been displaced seaward from its low fluvial discharge position. Because density circulation dominates over tidal pumping, the turbidity maximum becomes a more stable feature (both in location and concentration), through which a high yield of suspended matter is transferred to the bed of the estuary. Meade (1972) noted the

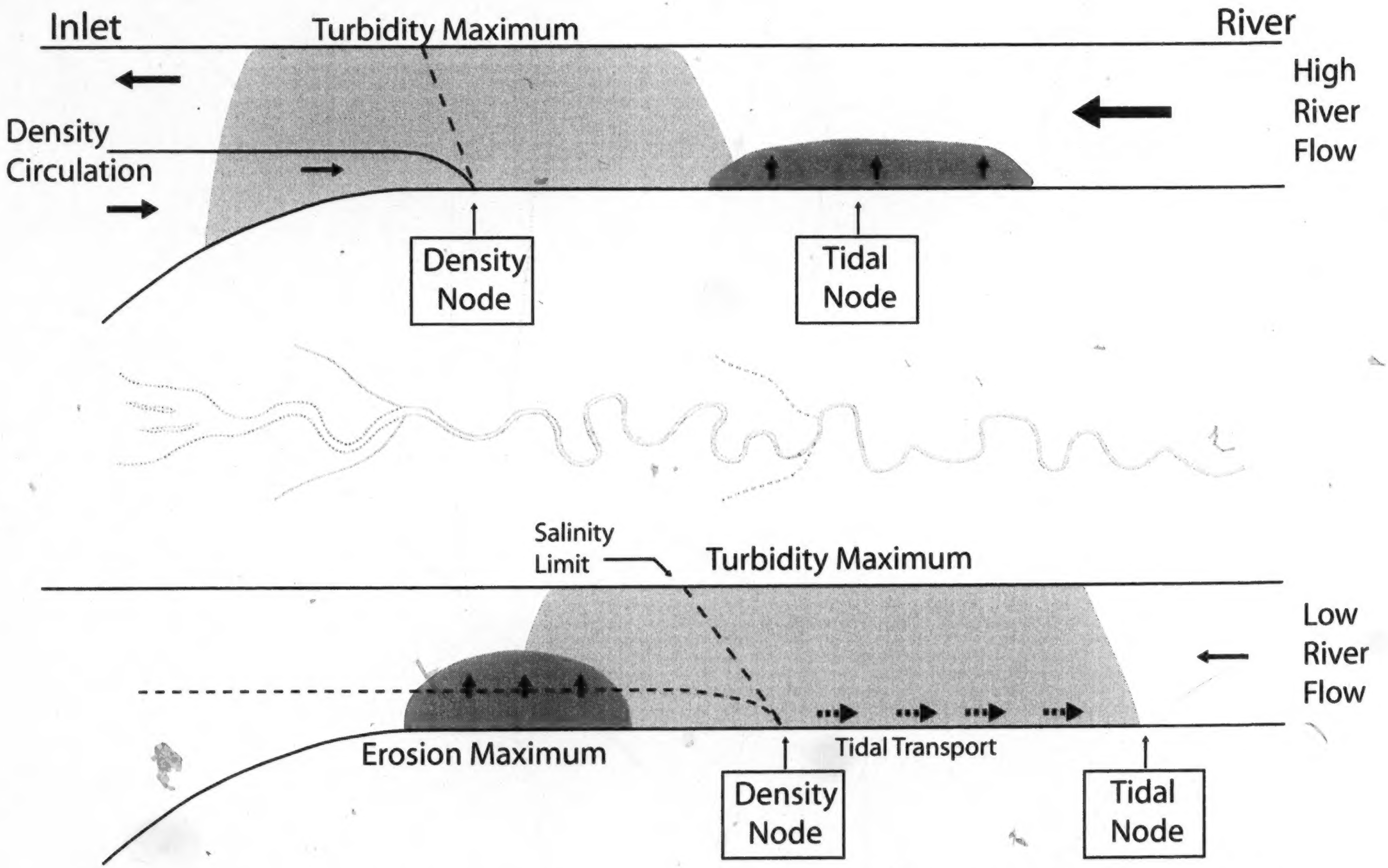


Figure 2.7 Seasonal variation in the location and behavior of the turbidity maximum within a partially mixed estuary. After Allen et al. (1980).

accumulation of fluid mud at the convergence of bottom water flow (salinity or density node) in association with high fluvial inflow, and the migration of this zone in association with changes in river discharge.

The dynamics of estuarine circulation and deposition also vary on an inter-annual basis as a result of low recurrence storm events. Such events lead to a complex evolution of water circulation processes, as the estuary is shocked by both a marine storm surge and subsequent extreme fluvial discharge. Nichols (1977) chronicled the response of the Rappahannock estuary to Tropical Storm Agnes.

Morphology

The mouths of many river systems are subject to tidal influence, owing to the tidal exchange of water within their intertidal channel reach. Such riverine estuaries typically display a tripartite zonation with respect to the plan form of the channel, commonly referred to as "straight-meandering-straight" morphology (Dalrymple et al., 1992). Moving upstream from the inlet, a fairly straight reach, characterized by mid channel and alternate, bank attached bars, passes into a highly sinuous reach exhibiting active channel migration. The high sinuousity reach then gives way to another low sinuousity reach as tidal influence dies out and fluvial influence dominates. In systems where the fluvial system feeding the estuary has a sinuous character itself, the estuary will exhibit a "straight-meandering" morphology (Eberth, 1996).

This morphologic character is seen in many modern estuaries, such as the South Alligator River and Ord River systems in Australia (Coleman and Wright, 1978; Woodroffe et al., 1989). While the rate of lateral accretion is greatest in the sinuous meandering zone, the growth of accretionary banks is also significant towards the fluvial end of the system, as well as in the outer, low sinuousity reach (Dellapenna et al., 2003).

The generation of a discrete zone of meandering within the channelized system appears to be an expression of the convergence of sediment transport within the system.

Dalrymple et al. (1992) noted that the zone of greatest meandering is associated with minimum sediment grain size and minimum total energy within the system. Typically this meandering zone is located upstream of tidal flat overbank deposition, in an area characterized by fluvial/alluvial overbank (Wright et al., 1975; Woodroffe et al., 1989; Allen, 1991).

The length of a riverine estuary is largely a function of coastal slope and tidal range, with relative length of the fluvial-dominated and tide-dominated reaches being a function of the balance between fluvial discharge and volume of the tidal prism (Dalrymple et al., 1992). The cross-sectional area of the channel decreases upstream as a result of the upstream decrease in tidal flux. This trend in cross-sectional area is coupled with a landward decrease in the radius of curvature through the meandering reach. While the systematic variation of cross-sectional area is seen in "graded" systems, some systems (e.g. the York River) (Dellapenna et al., 2003) have an anomalously deep and wide outer reach, characterized by greatly reduced rates of bank accretion. Such deviation from an equilibrium state may be a function of inherited, under-filled valley form. The general upstream shallowing of a riverine estuary is often punctuated by local over-deepening of the channel (leading to channel depths double or more that of the norm) due to excessive scour in areas of extreme curvature and confluence of tributary systems.

Transition in the character of overbank material is also seen along the estuarine channel. Near the inlet, overbank material consists of subtidal and intertidal flats. Towards the fluvial end, tidal overbank material gives way to fluvial/alluvial overbank material deposited during river flood.

The plan form of the estuary likely plays a major role in the dynamics of water circulation within the system. During times of high fluvial influx, when strong density circulation is set up, the density node must be found seaward of the high sinuosity zone. If it were found within this zone, flow around the meanders would tend to homogenize the water column and break up the circulation pattern.

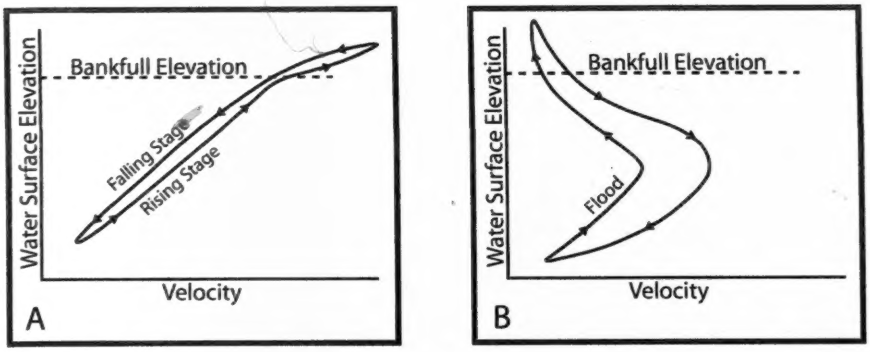


Figure 2.8. The relationship between water surface elevation and flow velocity for **(A)** a fluvial channel and **(B)** an ebb-dominated tidal channel. Note that within fluvial channels, overbank flow is associated with high flow velocity, while within tidal channels, overbank flow is associated with low flow velocity. From Eberth (2001).

Tidal Channel Morpho-dynamics

It is important to understand how morphology and dynamics of tidally influenced channels differ from channels of wholly fluvial origin. Contrasts in morphology are driven by two main differences in dynamics between fluvial and tidal channels: differing relation between water surface elevation and flow velocity, and the reversal of flow within tidal channels.

Within a fluvial channel, bankfull and overbank flow occur infrequently, and are associated with high flow velocity (Fig. 2.8). In a tidal channel, overbank flow occurs regularly and is associated with low velocity. This difference affects both the nature of overbank sediment, and the stability of the channel. In a tidal setting, the overbank material is typically finer grained than that in a fluvial setting (Table 2.1), and makes up a larger portion of the "floodplain" deposit. The low velocity associated with high water elevation in tidal channels leads to a lower occurrence of channel abandonment, particularly through chute cut-off and avulsion, relative to fluvial settings (Fig. 2.9). In a fluvial setting, the association of high water elevation, high flow velocity and sub-

Characteristic	**Environment**	
	Fluvial	**Tidal**
Channel		
Slope	Highly variable	Very low
Depth	Variable, up to 70m	varies with tidal range: mesotidal, 1-15m macrotidal, 1-30m
Network	Varies with structure, tectonics, climate	Dendritic, meandering
Point Bar	Crest inactive during normal flow	Crest active every tidal cycle
Chute	Subaqueous only during floods	Subaqueous through entire tidal cycle
Chute Bar	May be coarser than main bar	Rare, may be ebb- or flood-oriented
Sediment	Grain size varies, fine sand to pebbles	Grain size generally fine to medium sand
Bank		
Levee	Often well developed	Poorly developed to absent
Crevasse Splay	Often well developed	Absent or rare
Sediment	Sand, silt	Mud
Flood Basin		
Deposits	Point bar 60-90% Overbank 10-40%	Point bar <30% Overbank >70%
Preservation	Flood plain elevation modified by lateral erosion	Elevation of marsh tends toward MSL
Flood Frequency	<1/year	>6/month
Velocity		
Channel Maximum Velocity	Occurs near bankfull stages: usually >100 cm/sec	Flood: occurs before bankfull Ebb: occurs at lower stages than maximum flood velocity Usually <100 cm/sec
Overbank Average Velocity	Often competent to move medium sand	Competent to transport mud
Discharge	Highest at maximum river stage	Low near tidal extremes; maximum at intermediate stages
Suspended Sed. Concentration	Less than capacity at maximum discharge	Highest during maximum discharge (spring ebb)

Table 2.1. Comparison of morphologic and dynamic characteristics of fluvial and tidal channels. From Barwis (1978).

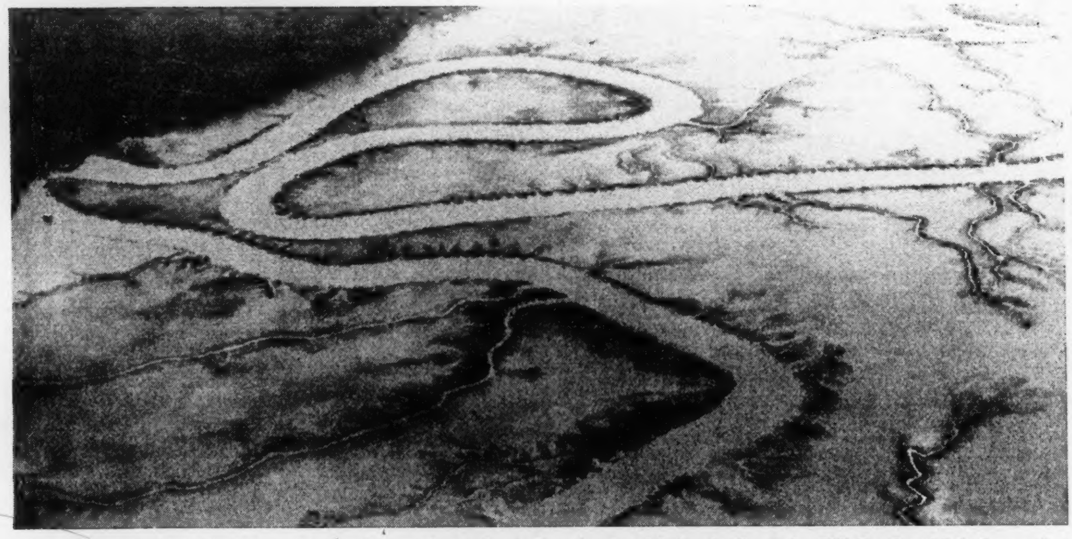


Figure 2.9. Aerial photograph of salt-marsh surface, Cumberland Island, Georgia. While the tidal channel has doubled back on itself, neck cut-off has not taken place. This illustrates the stability of channels subject to tidal flow dynamics. From Frey and Howard (1986).

capacity sediment load leads to the exploitation and expansion of overland flow paths during flood stage. This results in avulsion, chute cut-off, and a higher occurrence of neck cut-off. In a tidal setting, the association between high water elevation, low velocity, and high deposition from suspension leads to the infilling of overbank lows, and a much reduced incidence of channel abandonment.

Bidirectional flow within tidal channels complicates matters significantly over unidirectional fluvial flow. A shift in the loci of erosion and deposition between flood and ebb directed flow commonly leads to a segregation of flood- and ebb-oriented sedimentary structures. Additionally, the pathways followed by flood and ebb directed flow commonly diverge, leading to complex channel form. In the outer "straight" reaches of a tidal river, flood- and ebb-oriented flow commonly bifurcate, generating sub-channels separated by mid-channel bars. In sinuous reaches, point bars may develop a multi-lobed geometry in which an apical bar separates the outer, dominant current influenced channel from an inner, subordinate current influenced chute. In some systems, mid channel bars are well developed on the downstream sides of meander apexes (e.g. Frey and Howard, 1986). While common in purely tidal channels, the generation of multi-lobed and mid channel bars may be subdued within tidal rivers due to the regular disruption of bidirectional flow by high fluvial influx.

The character of accretionary bank deposition may change markedly over short distances, such as around a meander bend or between closely spaced bends. Smith (1987) noted that within the Willapa River, a coupled fining of sediment and shallowing of depositional dip is seen around a single point bar in a downstream direction (with respect to dominant current). Barwis (1978) noted that due to the segregation of flood and ebb directed currents, the orientation of sedimentary structures is commonly seen to contrast at different levels within the deposit of a tidal channel.

In a review of published IHS examples, the shape and slope of point bar surfaces are both seen to vary. While Smith (1988b) found dips of point bar surfaces in the Willapa River to be remarkably consistent from top to base, Edwards et al. (1983) found exhumed Permian point bars in north-central Texas to have a markedly concave-upwards form. In the latter case, the upward increase in dip was associated with an upward increase in mud content. Many authors have found the inclination of IHS strata to be highly variable within a given formation (Table 2.2). This variation may be explained through contrasting position along the accretionary bar, variations in radius of channel curvature, and variations in the textural makeup of the accumulating sediment, with the steepest dips associated with tight curves and cohesive sediment.

The presence of internal erosive surfaces (i.e. inclined surfaces within imbricate cosets) has been noted by several authors working with IHS deposits (e.g. Ramani, 1988; Eberth, 1996). Thomas et al. (1987) suggested that such surfaces may be generated through erosion of the point bar surface during extreme river floods or repeated chute cut-offs. Several additional allocyclic and autocyclic processes may also contribute to the generation imbricate cosets. These include extreme flow related to storm surges and rogue tides, inherent instability of point bar surface leading to gravity induced collapse, and changes in flow dynamics related to channel cut-offs immediately upstream or

IHS Set Thicknesses and Dips

Ancient

Locality	Thickness	Dip (degrees)	Ref.
Pleistocene Willapa Bay	10m	N/A	1
Upper Cretaceous Judith River Fm.	<20m (<13m typical)	1-29	2
Upper Cretaceous Bearpaw - Horseshoe Canyon Fm. Transition	<13m	8-15	3
Upper Cretaceous Horseshoe Canyon and Dinosaur Park Fm.	7-16m	<12	4
Lower Cretaceous McMurray Fm.	8-25m (20-45m channel)	4-22	5
Lower Permian Clear Fork Gp.	2-3m	5-25 (concave-up)	6

Modern

Locality	Thickness	Dip (degrees)	Ref.
Mesotidal Willapa Bay	7m	9-18	1
Macrotidal Daule River	12m	N/A	1
Macrotidal Babahovo River	15m	12	1
Macrotidal South Alligator River	10-15m	5-25	7
Macrotidal Ord River	av. ~12m (locally to 25m)	N/A	8
Microtidal York River	8-33m (under-filled relic valley?)	<2	9
Macrotidal Solway Firth (intertidal channels)	<3m	5-15	10

Table 2.2. A compilation of the thicknesses and dips of IHS sets within the rock record, and channel depths and accretionary bank inclinations within modern tidal channels. Note that the values of IHS set thickness and associated channel depth reported for the McMurray Formation are anomalously large. References: 1-Smith, 1988b, 2-Wood, 1989, 3-Rahmani, 1988, 4-Eberth, 1996, 5-Mossop and Flach, 1983, 6-Edwards et al., 1983, 7-Woodroffe et al., 1989, 8-Coleman and Wright, 1978, 9-Dellapenna et al., 2003, 10-de Mowbray, 1983.

downstream.

Channel Migration

The migration of a meandering channel may take place in either a confined or unconfined manner (Fig. 2.10). Where the migrating channel is contained within a strict meander belt that does not exceed the natural amplitude of the channel (e.g. within a narrow valley), the expansion of meanders is precluded, and channel migration is limited to translation in the direction sediment flux along the axis of the belt. Where a migrating channel is not confined (e.g. within a wide floodplain of poorly consolidated sediment), the channel is free to migrate through expansion and rotation of meander bends as well as translation. With confined migration, the resultant accretionary surfaces are limited in orientation such that they dip obliquely down the meander belt. With unconfined migration, the resultant accretionary surfaces have no directional organization. Odguard (1987) suggested that within fluvial systems, the prevalence of meander expansion and downstream translation are respectively linked aggradation and degradation (i.e. local sedimentation and sediment by-pass).

As mentioned earlier, within a riverine estuary, sinuous channel meandering is limited to a central zone, with less sinuous reaches upstream and downstream. Within three modern systems along the Australian coast, the Ord River, the South Alligator River and the Daly River (Coleman and Wright, 1978; Woodroffe et al., 1989; Chappel, 1993), sinuous channel meandering takes place in an area approximately 5-10 km wide and 15-20 km long, with relic meander forms preserved in a zone stretching10's of km inland. This implies system progradation since the end of the Holocene transgression, with a seaward shift on the order of 5 km per millennium.

The factors controlling migration rate of meandering channels have been dealt with qualitatively by several authors. Odguard (1987) suggested that erosion of a vegetated cutbank takes place at roughly half the rate of an unvegetated bank, and cites

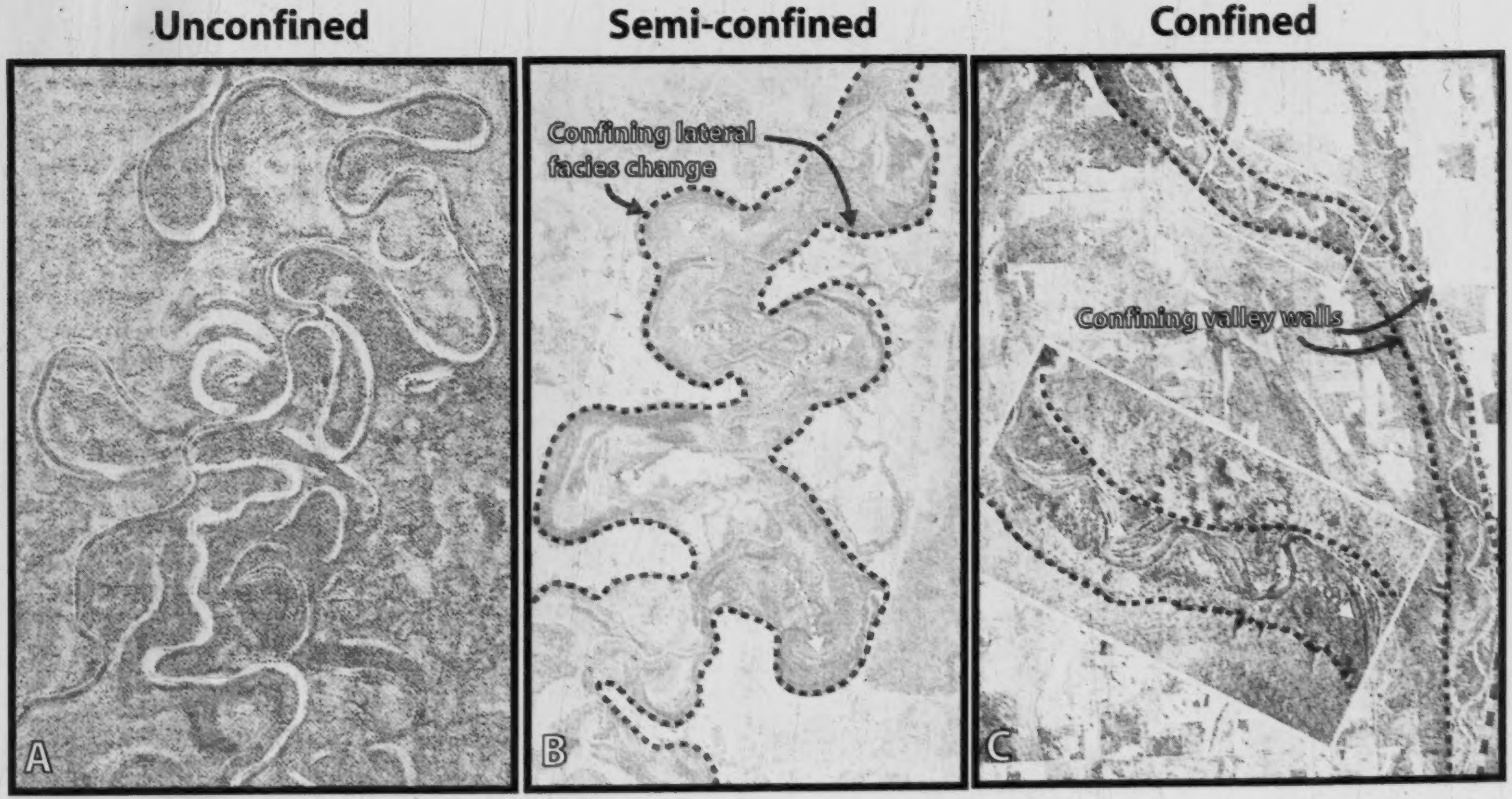


Figure 2.10. Variations in the pattern of channel migration related to bounding conditions. **(A)** Channel is not confined, and channel migration has taken place in a disordered fashion. Hay River, Alberta. **(B)** Channel is confined by a cohesive 'host' facies, resulting in the creation of discrete meander 'pods', which have been repeatedly reoccupied with a consistent point bar geometry. Location unknown. **(C)** Channel is confined within a narrow valley, which limits channel migration to translation of meanders along the axis of the valley. Beaver River, Alberta.

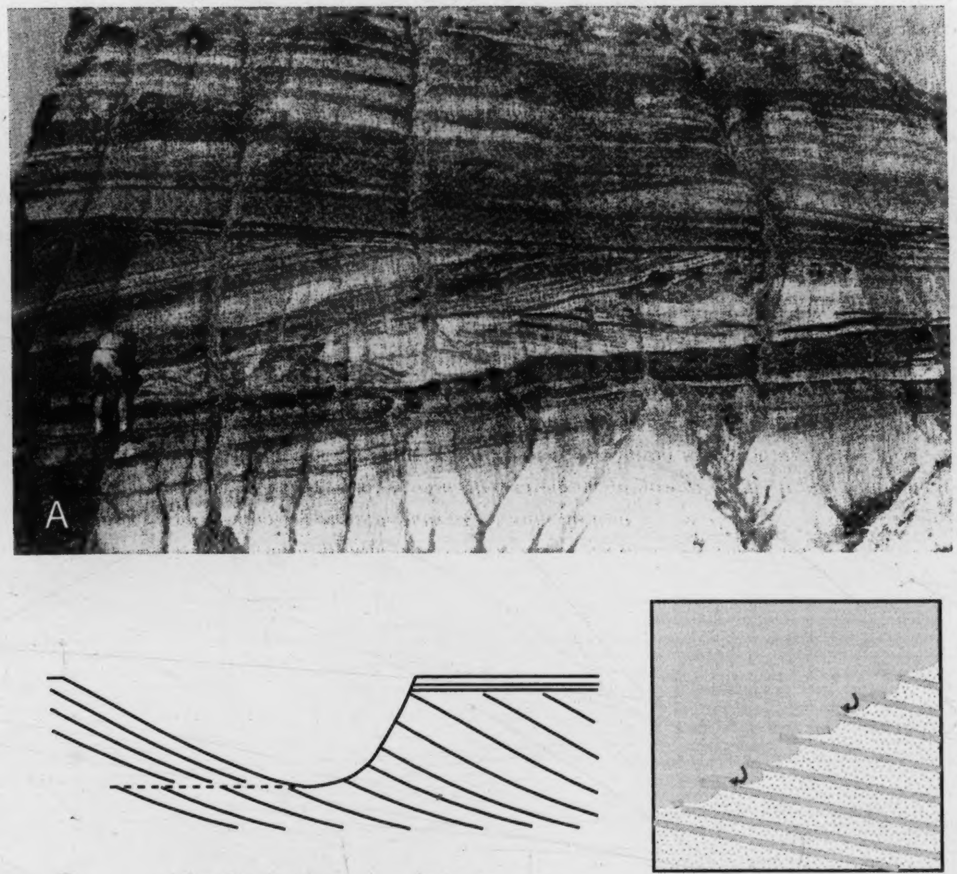
fluvial meander migration rates of approximately 1% of channel width annually. The ratio between channel width and radius of curvature around meander bends may also play a significant role in determining cutbank erosion rate (Jackson, 1976). Barwis (1978) found migration rates in tidal channels to vary greatly, largely under the influence of cutbank lithology. Ikeda (1989) stated that "plan form and migration of meandering channels is strongly influenced by the distribution of thick, fine grained, cohesive flood plain deposits".

The character of sediment through which the channel is cutting may influence the depth and cross-sectional profile of the channel in addition to its plan form. The role peat layers play in limiting the depth of channel incision has been highlighted by Eberth (1996) in the Upper Cretaceous of southern Alberta, and by Ryer and Langer (1980) in the Upper Cretaceous of central Utah. Beds of cohesive mud have a similar effect on limiting incision depth, and a particularly relevant example from the Judith River Formation (Fig. 2.11A) was presented by Thomas et al. (1987). In this example, an IHS set bottomed-out against a thick inclined mud bed, and climbed up along the mud bed, pinching thinner and thinner. This implies that IHS sets containing cohesive mud layers possess anisotropic susceptibility to erosion during subsequent channel migration. This would lead to the preferential generation of stacked cosets with similar accretion direction, and low incidence of stacked cosets with opposing accretion direction.

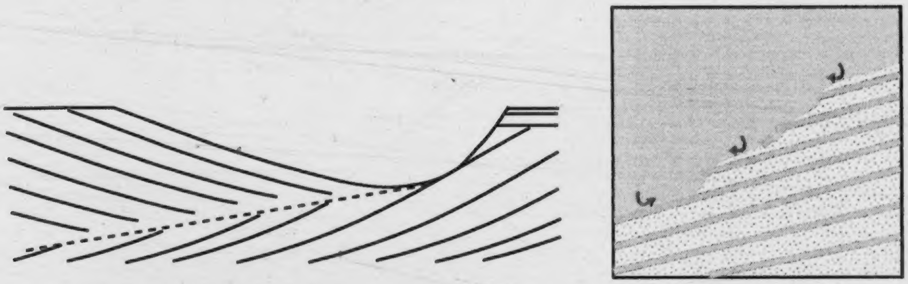
Wood (1989) presented a useful discussion of the genetic behavior of lateral accretion packages within the upper Cretaceous Judith River Formation, particularly with respect to their initiation, termination and stacking.

THE EFFECT OF SYSTEM DYNAMICS ON BENTHOS

Low absolute salinity, rapid salinity fluctuation, high turbidity and shifting substrate are all known to play significant roles in limiting benthic colonization, and influencing the behavior of those organisms which do establish themselves. As such, the



B All cohesive layers undercut
Channel maintains depth



C Cohesive layers at base not undercut
Channel cannot maintain depth

Figure 2.11. Anisotropic erosional susceptibility of IHS with cohesive mud beds. **(A)** An example from the Upper Cretaceous Judith River Formation showing a small IHS set climbing an inclined mud bed. From Thomas et al. (1987). **(B)** Where a channel is migrating with the same directional sense as the IHS through which it is cutting, mud beds are undercut and the channel maintains depth. **(C)** Where a channel is migrating with opposing directional sense to the IHS through which it is cutting, it cannot undercut mud beds near its base, and thus cannot maintain depth.

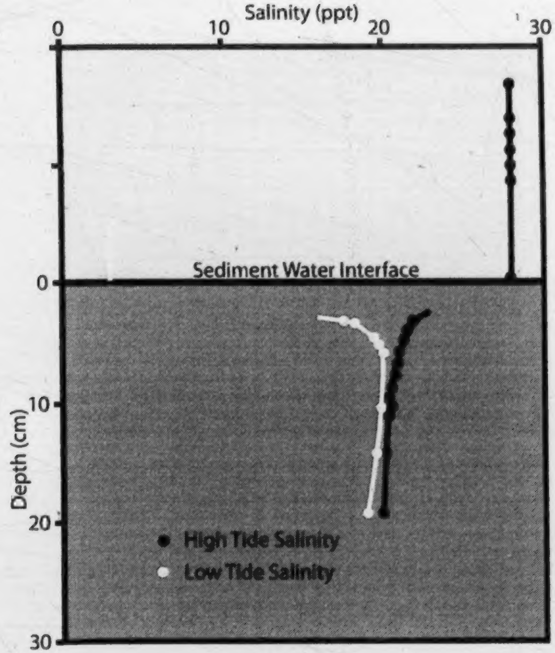


Figure 2.12. Tidal variation in salinity within the water column and sediment pore space. Note how the sediment acts as a buffer against salinity fluctuation. From Knox (1986).

dynamics of estuarine circulation play a significant role in dictating the distribution of benthic organisms and their activities, in both a spatial and temporal sense.

Due to the rigors of maintaining proper cellular chemistry, the estuarine environment can be harsh on aquatic organisms. Various groups of aquatic fauna have made adaptive changes that allow them to tolerate varying ranges of absolute salinity and rates of salinity fluctuation. Many of these adaptations involve biotic processes on the cellular level that allow the organism to tolerate exposure to salinity stress. Other adaptations are behavioral and reduce the organism's exposure to stress. Deep infaunal burrowing minimizes exposure to salinity variation in the overlying water column through the buffering effect of the sediment pore water (Fig. 2.12). Other adaptive behaviors include reduced activity during low salinity portions of the tidal cycle, and the closure of bivalved organisms, with the entrapped water acting as a buffer.

Within estuaries, the nature and intensity of salinity stress is seen to vary along the system. In the far outer reaches of an estuarine channel, stress is low owing to stable, near marine salinity. In the mid-outer reaches, absolute salinity is moderately reduced relative to marine levels, but again, salinity fluctuation is minimal. In mid-inner reaches, absolute salinity is significantly reduced and diurnal fluctuation is pronounced. In far inner reaches, salinity is fairly stable, showing little elevation over that of freshwater. Howard et al. (1975) showed quite clearly within the Ogeechee River – Ossabaw Sound system of Georgia how a gradient in salinity stress affects the abundance and diversity of resident benthic organisms (Fig. 2.13). A general decrease in diversity is seen with decreasing absolute salinity, and a minimum of abundance is seen in the region exposed to the most pronounced semidiurnal fluctuation in salinity.

Other factors, such as water turbidity, rate of sedimentation and the texture and stability of substrate can also have a great effect on the viability and behavior of benthic organisms. Because the various stresses vary spatially within the estuary, position can greatly influence the behavior of resident organisms. For example, near the mouth of the system, a sandy substrate, hospitable salinity and low turbidity will promote the activity of filter feeding organisms, with burrows open to water column. At a position further landward, high turbidity, extreme salinity fluctuation and a muddy, organic-rich substrate will promote the activity of endobenthic deposit feeders.

As circulation and sedimentation evolve through annual cycles, the stresses at a given location within the estuary will vary. Near the mouth of the system, filter feeders will be highly active during periods of low fluvial discharge, but will be snuffed out by the seaward excursion of the turbidity maximum during high discharge. In positions midway up the estuary, quiescent conditions of moderate salinity may be replaced by high energy fluvially driven processes and freshening of water chemistry during periods of high discharge.

The preservation potential of bioturbation may be unequal along the system, and lead to situations where locations rich in biologic activity pass little evidence of such into the rock record. Howard et al. (1975) showed that within the channelized portion of the Ogeechee River – Ossabaw Sound system, the most seaward point bars exhibited active

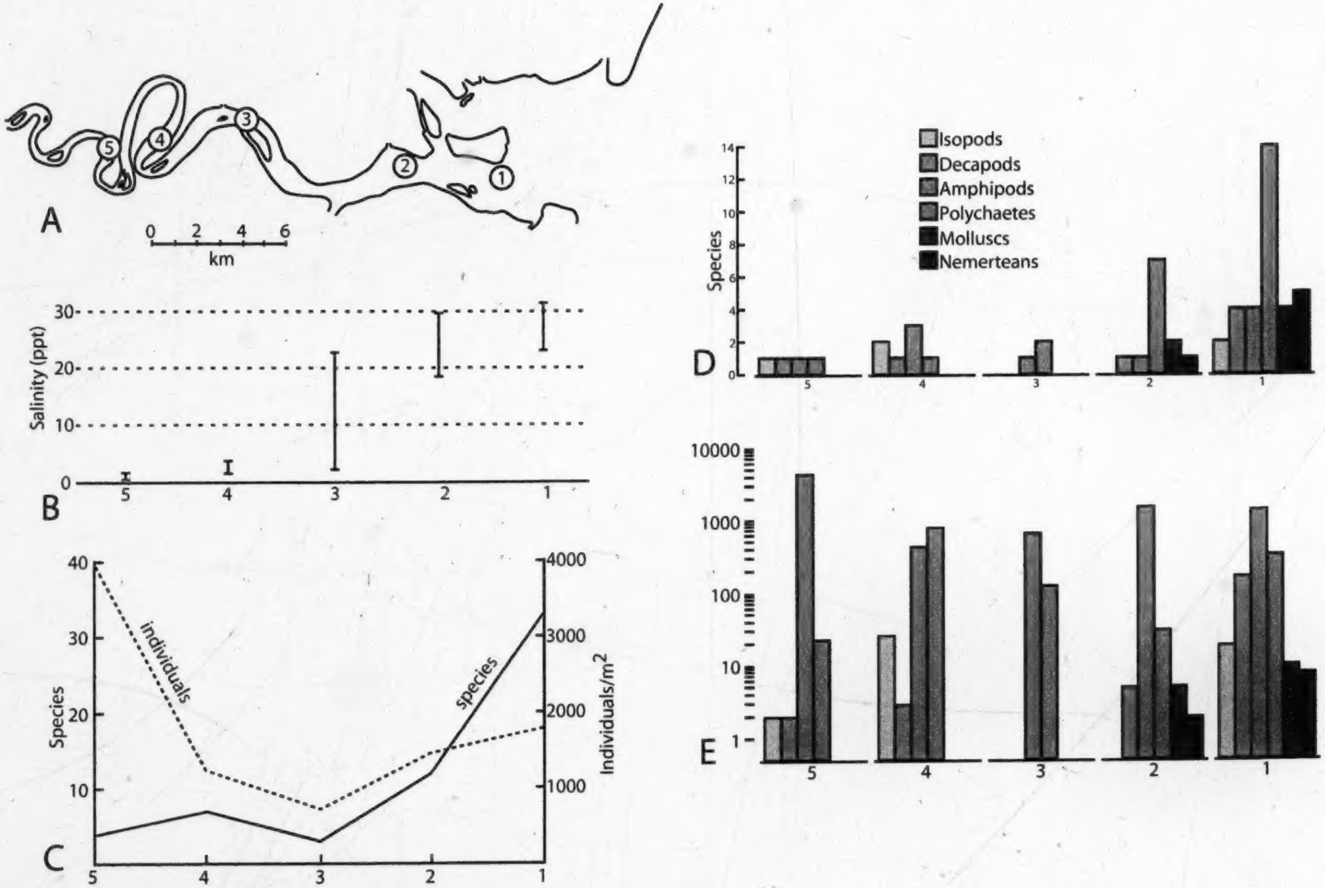


Figure 2.13. The effects of water salinity variation within the Ogeechee River – Ossabaw Sound estuary. **(A)** Plan form and station location. **(B)** Semidiurnal range of salinity at each station. **(C)** Abundance and diversity of the benthic community along the system. **(D)** Systematic organization of diversity. **(E)** Systematic organization of abundance. Modified from Howard et al. (1975).

colonization, but little evidence of such was preserved below the surface. This paradox was attributed to frequent physical reworking of this sub-environment through high energy wave and tidal current action. In examining the rock record, the effects of repeated destruction of biogenic structure in high energy environments must not be overlooked.

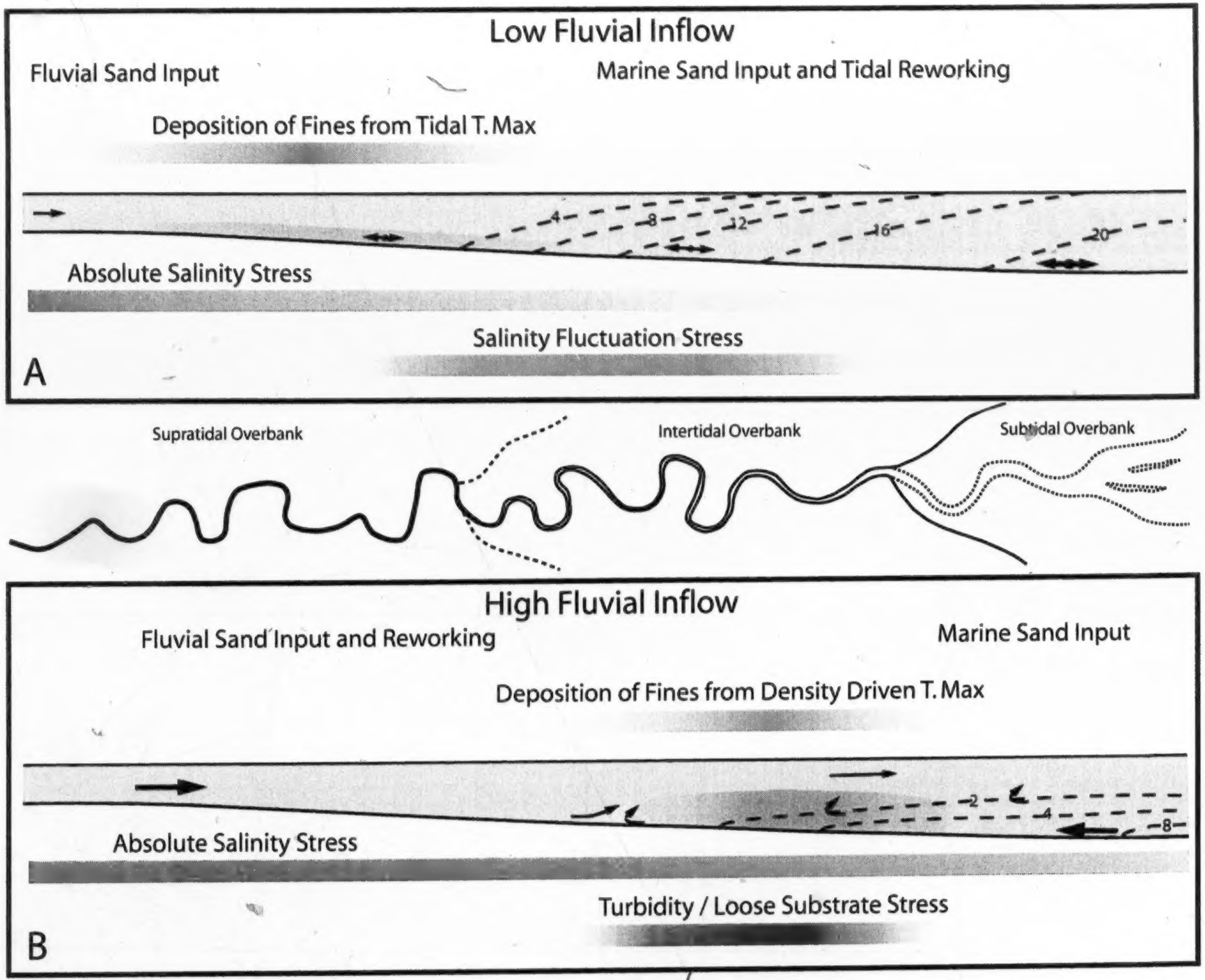
SYNTHESIZED DEPOSITIONAL MODEL

With an understanding of the processes driving and controlling sedimentation in an estuary, it is possible to generate a model that predicts longitudinal variation in depositional character along the system (Fig. 2.14).

Near the head of the system, high river discharge brings high energy and sediment load, resulting in the accumulation of high energy, rapidly emplaced sands with fluvial character. During periods of low river discharge, this area is the locus of a low intensity, transient turbidity maximum maintained landward of the density node through tidal action. Deposition from the tidally maintained turbidity maximum is likely to be dominated by finely laminated, low energy deposits with a tidal character. Due to the high energy associated with fluvial flooding, the finely laminated deposits would be vulnerable to erosive removal, leading to common amalgamation of fluvial sands.

Towards the inlet of the system, high fluvial discharge will bring a seaward displacement of the density node, and a strengthening of density circulation. This, coupled with a high influx of suspended material from continental drainage, will lead to the establishment of a high concentration, stationary turbidity maximum in the area. Large volumes of fine material will be deposited in a relatively unstructured manner from the turbidity maximum, which is maintained through density circulation. During periods of low river discharge, the area will be dominated by moderate to high energy tidal processes, and higher absolute salinity. This higher energy will lead to scouring of the previously deposited muds, and subsequent deposition of sands driven inland from the inlet by tidal flow.

Figure 2.14. Contrast in estuarine circulation, sedimentation and biologic stresses between periods of low river discharge and high river discharge. **(A)** During periods of low river discharge, tidal circulation dominates over fluvial/density circulation. The system experiences a deep incursion of brackish water. Deposition of fines is skewed towards the fluvial end of the system and takes place with a laminated tidal character. The inlet end of the system experiences tidal reworking with a net landward flux of sediment. **(B)** During periods of high river discharge, fluvial/density circulation dominates over tidal circulation. Brackish water is flushed from much of the system. Deposition of fines is skewed towards the inlet end of the system and takes place with a largely unstructured character. The fluvial end of the system experiences intense reworking with a net seaward flux of sediment.


Low Fluvial Inflow
Fluvial Sand Input
Marine Sand Input and Tidal Reworking
Deposition of Fines from Tidal T. Max
4
8
12
16
20
Absolute Salinity Stress
Salinity Fluctuation Stress
A
Supratidal Overbank
Intertidal Overbank
Subtidal Overbank
High Fluvial Inflow
Fluvial Sand Input and Reworking
Marine Sand Input
Deposition of Fines from Density Driven T. Max
2
4
8
Absolute Salinity Stress
Turbidity / Loose Substrate Stress
B

Within the center reach of the system, low to moderate energy will dominate throughout the cycle, and fine sediment character will be transitional between that seen at each end of the system. In this region deposition will be influenced by the turbidity maximum as well as moderate energy pulses driven by high fluvial inflow and periods of strong tidal forcing. During periods of low fluvial discharge, salinity will fluctuate with diurnal tidal flow.

OBSERVATIONS AND INTERPRETATIONS

PURPOSE AND METHOD OF STUDY

In order to demonstrate the breadth of character inherent to IHS of the McMurray Formation, intervals of twenty eight cores (representing approximately 900 m of section) from Canadian Natural Resource Limited's Horizon Project lease were logged. Additionally, several outcrops were examined. In studying IHS within the McMurray Formation, core and outcrop each have inherent strengths and weaknesses.

Core presents a continuous, one-dimensional sampling of rock, free of erosional effects and lithologic preservational bias. The proper identification of IHS in core may be challenging, but is facilitated when accompanying dipmeter logs are available. The geometry and significance of discontinuity surfaces seen in core is unclear, and no doubt many such surfaces are too subtle to be readily identified. Due to pervasive bitumen stain, the structure of clean sand beds is typically obscured.

Outcrop provides a two-dimensional section through the rock, allowing for a more instructive examination of morphologic features within the rock, such as the shape and stacking pattern of IHS sets. Structure within the sand is typically enhanced through weathering effects. The usefulness of outcrop is limited by several factors, including: accessibility, incomplete exposure, limited geographical distribution, a preservational bias towards sand-dominated deposits and weathering effects within mud-rich horizons.

The examination of mine-face exposures would overcome several of these limitations, but owing to logistical and safety considerations, no significant campaign of mine-face examination was undertaken for this study.

CHARACTERIZATION OF McMURRAY FORMATION IHS

Within the McMurray Formation, a number of IHS lithosomes with distinct sedimentologic and ichnologic character are seen. Of these, five can be clearly related to depositional dynamics along the main axis of a riverine estuary.

Lithosome A

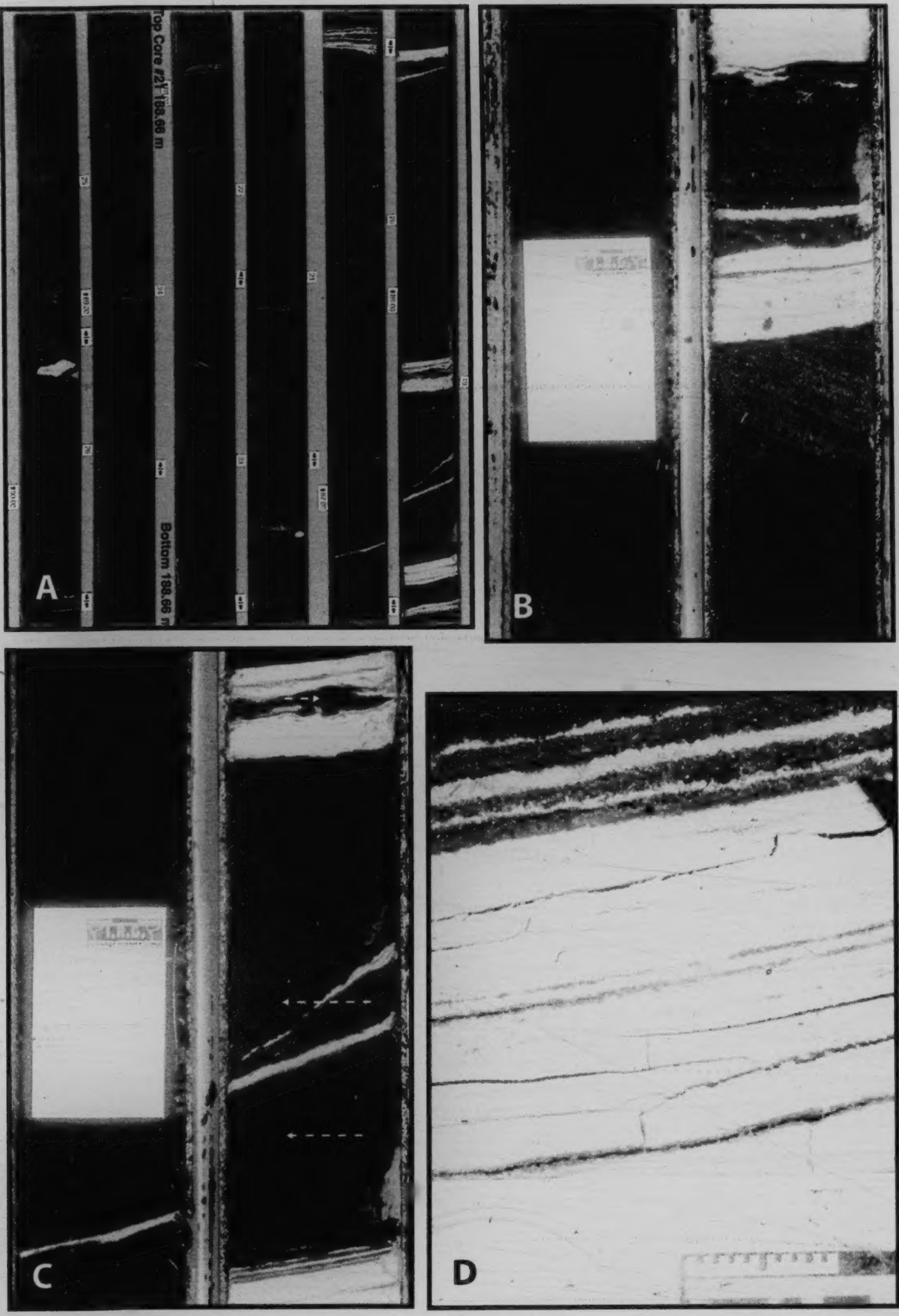
This lithosome consists of sand-dominated IHS containing coarse members of inconsistent thickness, and fine members commonly displaying starved interlamination of mud and silt/sand (Fig. 2.15A). Coarse-fine member contacts are sharp, and burrowing is near absent. The single encountered example succession is broken by clear discontinuities into several sets, none of which exceed 5 m in thickness.

Coarse members are typically composed of relatively poorly sorted lower very fine to lower fine sand, and vary in thickness from 5 cm to in excess of a meter. Where clear, structure includes ripple cross-stratification, cross-bedding on a 5-40 cm scale and parallel bedding (Fig. 2.15B). No clear hierarchy of structure is seen within the coarse member beds. Some cross-beds are highlighted by concentrations of mud chips and carbonaceous debris within their toesets, or drapes of massive mud (<1 cm thick) within their foresets (Fig. 2.15C).

The coarse members are devoid of evident burrowing.

Fine members vary significantly in character and thickness. Some fines are composed of a single layer of massive mud up to 3 cm thick, some display ultra fine interlamination of mud and silt/sand (Fig. 2.15D), while others show mm- to cm-scale

Figure 2.15. Character of Lithosome A. All from AA/15-23-96-13 W4. **(A)** Sand dominated IHS. Base of the core is to the lower left, top to the upper right. Note the inconsistent thickness of coarse members, variable character of the fines, and subtle expression of cross-bedding in the sands. The mud and carbonaceous clast-bearing horizon just above 190 m marks a clearly erosive contact, thought to represent a channel base. **(B)** Sharp contacts between coarse and fine members. Note the robust cross-bedding in the sand, and the sand-starved nature of the fines. 185.3 m. **(C)** Intra-member mud drapes highlighting otherwise obscure cross-bedding in the sand. Note that the ripple bedding in the overlying fine member indicates an opposition of sediment flux between coarse and fine member deposition. 187.0 m. **(D)** Fine lamination with respect to the content of silt/sand in fine member mud. Note that most of the granular material in the mud is considerably finer than that seen in the overlying sand bed, while that seen in the better developed, bitumen-stained laminae is of equivalent coarseness. 186.5 m.


A
Top Core #21 188.66 m
Bottom 188.66 m
B
C
D

interlamination of fairly massive mud and clean sand (Fig. 2.16A). In some cases mud and starved ripples of silt/sand are found in intimate association, either as ripples with ultra thin mud drapes in their foreset laminae (Fig. 2.16B), or as isolated ripples encased in mud (Fig. 2.16C). In general, the fine members exhibit starvation with respect to the availability of granular material, reflecting extremely low competency of flow during fine member deposition. Internal variations in the character and texture of the fine members are quite common, locally exhibiting a cyclic nature suggestive of fortnightly variation in sedimentation (Fig. 2.16D).

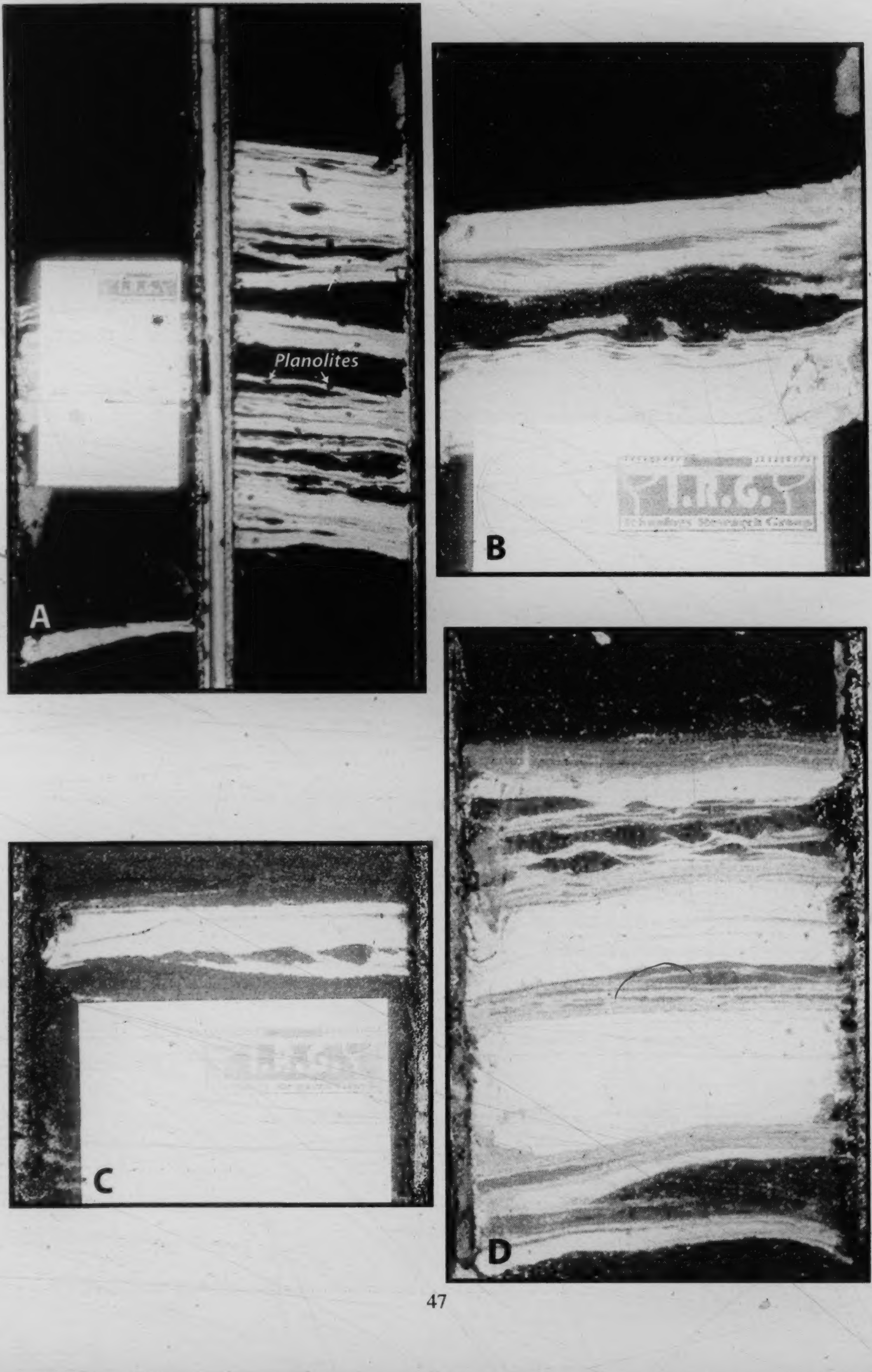
Burrowing is extremely rare in the fine members. *Planolites* is found exclusively and is typically less than 3mm in diameter.

Contacts between the coarse and fine members are typically sharp. Opposition of bedform migration direction between fine and coarse members is apparent locally.

This succession displays no significant vertical trends. The sand is relatively coarse and poorly sorted throughout the succession, and no trend in the scale of cross-stratification is apparent. Broken up into numerous sets less than 5m in thickness, the dipmeter data displays inconsistent orientation between sets and poorly organized profiles within them.

Observations are consistent with deposition near the landward limit of tidal influence, where fluvially driven deposition dominated and low energy tidally driven deposition took place only during periods of negligible fluvial input. Three characteristics suggest that the coarse members were deposited under conditions of suppressed salinity relative to the fine members. First, synaeresis cracking, commonly seen in other IHS species in association with fine to coarse member transitions, is not seen. Secondly, the paucity of muddy laminae within the sands suggests that salinity induced flocculation did not take place during coarse member deposition. Thirdly the absence of burrowing in coarse members may reflect inhospitably low salinity, whereas limited burrowing

Figure 2.16. Character of Lithosome A. All from AA/15-23-96-13 W4. **(A)** Fairly coarsely interlaminated mud and sand, displaying moderately abundant *Planolites*. This thick fine member contains the most abundant burrowing seen in the IHS succession. Note the alternation between clean sand and dense mud deposition with little intermediate material. 179.6 m. **(B)** Close up of the fine member seen in Figure 2.15-C. Note the repeated appearance of fine mud laminae completely draping the accretionary face of the ripple. This implies cyclic, possibly tidal, variation in the competence/sediment load of the causative flow. 186.1 m. **(C)** Ripples encased in mud and fine mud chips. Note the cyclic variation between sand and mud chip deposition, suggestive of tidal influence. The ripples are capped by a dense mud layer deposited through suspension fallout. 181.4 m. **(D)** Cyclic variation in the character and silt/sand content of fine member deposits. This example is strongly suggestive of fortnightly tidal variation in the competence of flow. 184.0 m.


Planolites
A
T.R.G.
B
C
D

in the fine members may indicate a notable rise in salinity. The sharp contacts seen between fine and coarse members indicate that changes in the dynamics of deposition (and possibly water chemistry) were punctuated. The inconsistent thickness of coarse members is thought to be the result of irregularity of depositional dynamics in the form of inconsistent thickness of coarse member deposition, irregular development of fine member depositional conditions (allowing for conformable amalgamation of sand beds), and amalgamation of sands through erosion of intervening fine members.

The fine members display character consistent with tidal influence, with the alternation between mud deposition and starved ripple formation. In several examples, this alternation is suggestive of fortnightly variation in flow competence. Locally, opposition of bedform migration between coarse and fine member deposition in seen, which is consistent with a basinward sediment flux during coarse member deposition, and landward flux during deposition of fines. The limited endogenic burrowing within the fines suggests that salinity within the water column was unstable during times of fine member deposition.

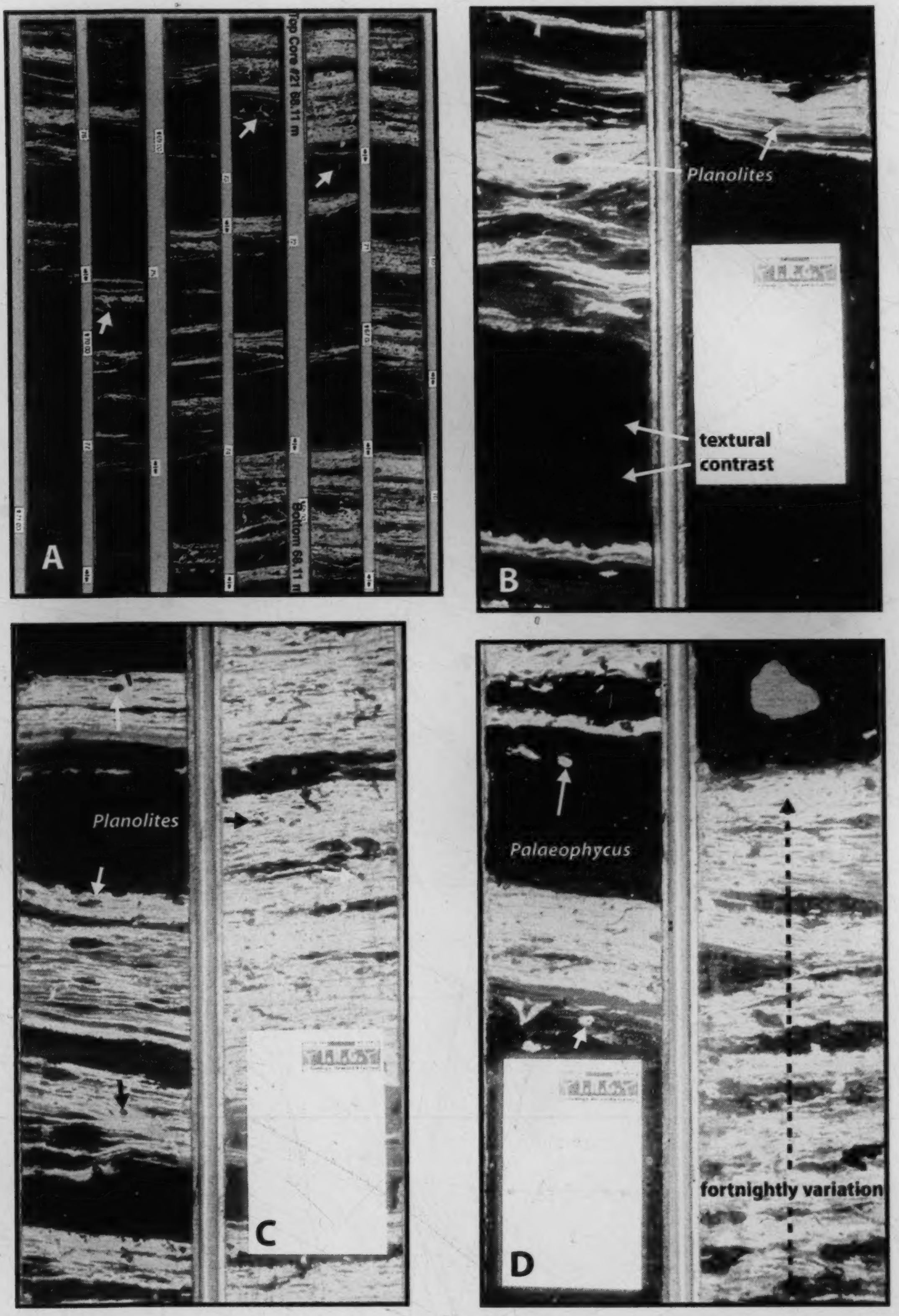
Low stability of channel and bank morphology are indicated by the presence of numerous discontinuities within the succession, and the variable orientation of the sets they define.

Lithosome B

This IHS lithosome shows a gradational upward muddying trend, with the fine members displaying clearly tidal character (Fig. 2.17A). Low diversity burrowing is fairly abundant in the fine members, while bioturbation is rare in the coarse member sands. The example succession consists of two individual IHS sets, 6 and 10 m thick, which have broadly consistent character and orientation.

Coarse members are composed of a fairly poorly sorted mix of silt and very fine sand and typically range in thickness from a 3 - 15 cm, with adjacent beds often

Figure 2.17. Character of Lithosome B. All from AA/01-06-97-11 W4. **(A)** Upward muddying IHS. Base of the core is to the lower left, top to the upper right. Note the interlaminated nature of the fines, and common muddy burrows subtending from the fines into underlying sands. **(B)** Inconsistent texture of coarse member material. The coarse member to the left of the scale card is composed of two texturally contrasting beds. 69.8 m. **(C)** Fine lenticular interlamination of the fine member material. 63.7 m. **(D)** Rhythmic variation in the granular content of fine member material suggestive of fortnightly tidal variation in flow strength. 66.5 m.


A
Top Core #21 88.11 m
Bottom 88.11 m
B
Planolites
textural
contrast
C
Planolites
D
Palaeophycus
fortnightly variation

contrasting somewhat in texture (Fig. 2.17B). Locally, coarse member beds are composed of amalgamated upward fining cycles. Ripple cross-lamination on a 1 – 3 cm scale is common.

The coarse members are generally unburrowed, although rare indistinct mottling is seen.

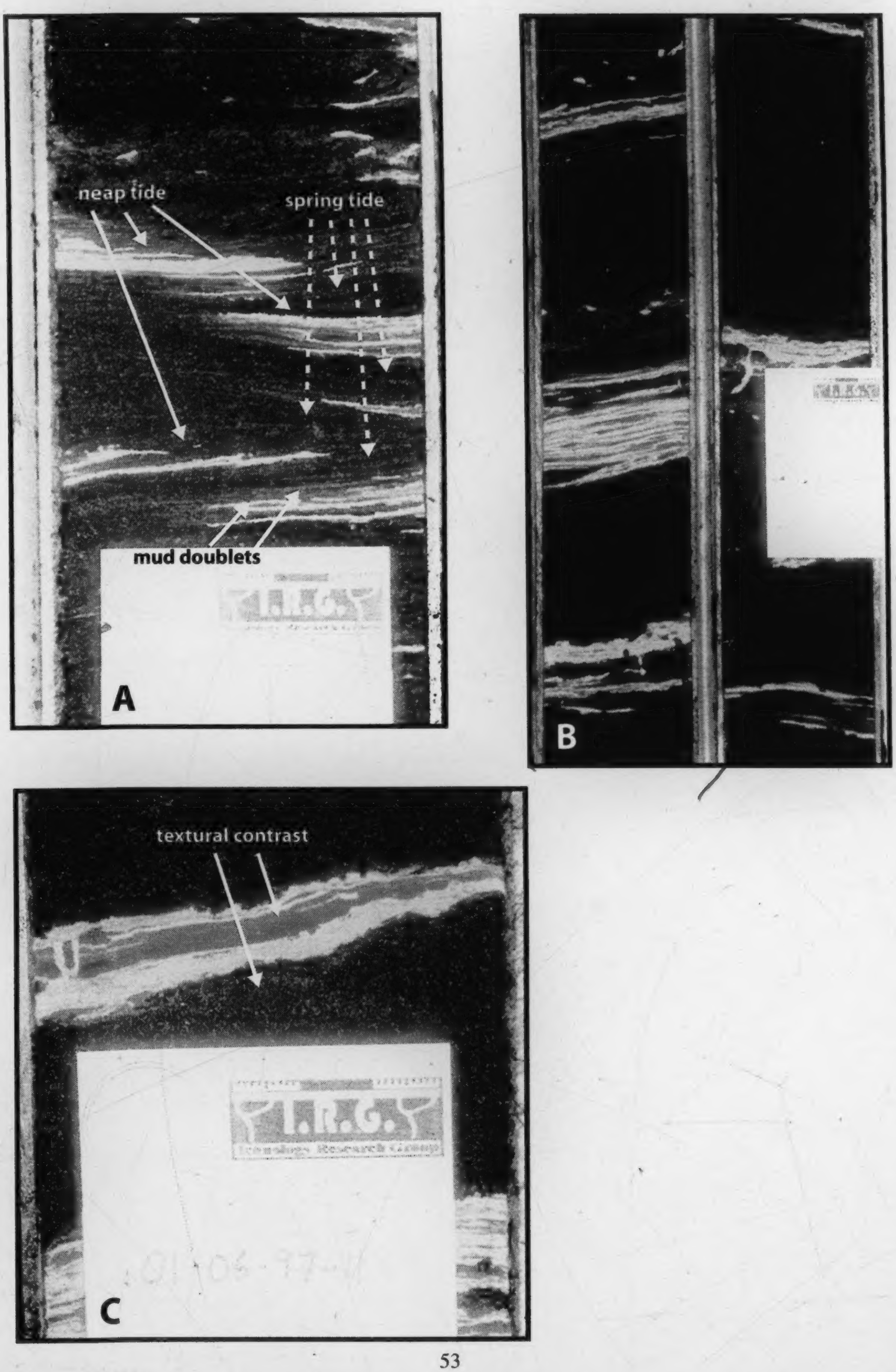
Fine members are composed of finely lenticularly interlaminated mud, silt and lower very fine sand (Fig. 2.17C). The interlamination is often rhythmic in nature, and suggestive of fortnightly tidal cyclicity (Fig. 2.17D). In several places clear mud doublets and double mud-draped ripples are seen (Fig. 2.18A).

Burrowing within the fine members is moderately abundant and dominated by *Planolites*. In places, muddy inclined burrows and *Palaeophycus* are seen to subtend from the fines into the tops of underlying coarse member sands.

The inclined units remain fairly consistent in thickness (Fig. 2.18B), while the thickness and proportion of fine members increase upwards at the expense of the coarse members. Contacts between the coarse and fine members may be sharp or transitional, with the bases of thicker coarse member sand beds tending to be quite sharp. Coarse and fine members are locally seen to contrast strongly in the texture of their granular components (Fig. 2.18C). Synaeresis cracks are reasonably common towards the top of the succession, and are found in association with the transition from muddy to sandy deposition.

Observations are consistent with deposition in a position intermediate between the seaward and landward limits of turbidity maximum excursion. The variable texture of the coarse members sands, coupled with the rarity of burrowing is suggestive of fluvial deposition for most of the coarse members. The presence of synaeresis cracks suggests that some coarse members were deposited in association with comparatively high salinity, likely through tidal forcing during periods of extremely low fluvial inflow. The

Figure 2.18. Character of Lithosome B. All from AA/01-06-97-11 W4. **(A)** Tidal variation in the mud content of an aggradational bedform. Fine mud laminae occur in pairs, reflecting semidiurnal cyclicity, while the proportion of mud varies, reflecting fortnightly cyclicity. 70.2 m. **(B)** Fairly consistent inclined unit thickness. 73.0 m. **(C)** Contrasting grain size of granular material between coarse and fine members. This implies a wholesale change in the competence of flow between coarse and fine member deposition, and possibly a change in sediment flux direction. 73.4 m.


neap tide
spring tide
mud doublets
A
B
textural contrast
C

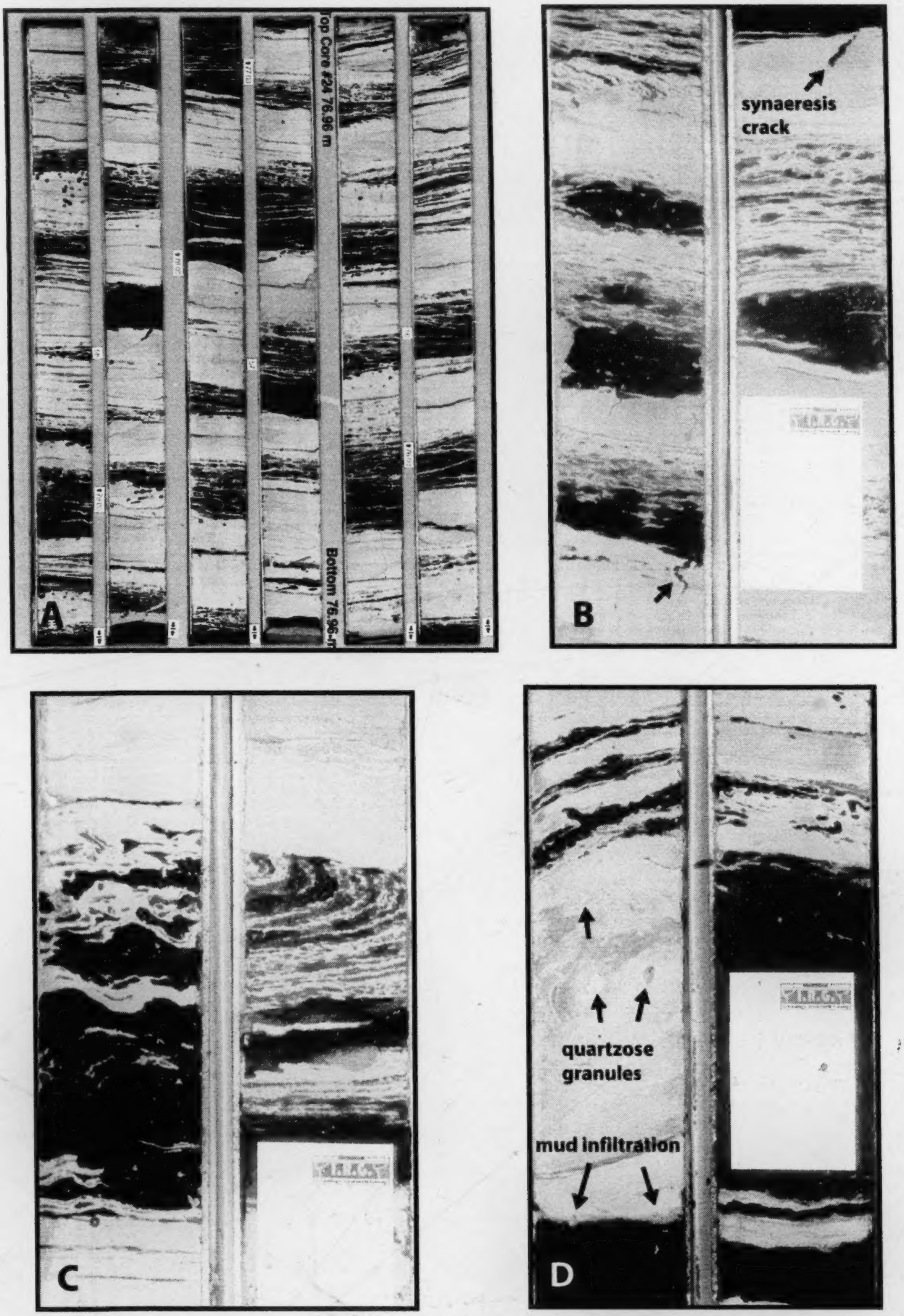
amalgamation of upward fining cycles within the coarse members may reflect deposition from subsequent fluvial flood events. Moderately abundant burrowing in the fine members, and the abundance of fine mud laminae indicate deposition under the influence of saline water, although the dominance of endogenic forms suggests that salinities were unstable. Double mud drapes, mud doublets and rhythmic variation in the granular content of the fines indicate deposition took place under low energy tidal conditions. The contrast in granular grain size between the coarse and fine members indicates drastic change in the competence, and likely flux direction, of sediment transport. All in all, observations suggest that deposition took place where moderate energy fluvial processes exerted influence, but were tempered by an overall brackish estuarine environment.

Lithosome C

This mud dominated lithosome is comprised of interbedded dense muds and flaser-bedded to locally clean sands (Fig. 2.19A). The thickness of the inclined units is strikingly consistent within a given set. Coarse-fine member contacts are gradational to sharp, and burrowing is present in both fine and coarse members. Deformation, seen as both distortion of laminated material and churned muddy slump deposits, is quite common (Fig. 2.19C, D). Example successions range up to 37 m thick, but can typically be broken into several thinner sets.

Coarse members are composed of well sorted silt to upper very fine sand (locally to lower fine sand), commonly interlaminated with mud. Character of the coarse members varies from lenticularly interlaminated silt/sand and mud horizons a few mm to a few cm thick, to flaser interbedded silt/sand and mud in horizons 2 – 20 cm thick, to occasionally developed clean sand beds, typically less than 5 cm thick (Fig. 2.19B). Locally the coarse members are expressed only as silt/sand-rich burrowed horizons in the otherwise structureless mud, exhibiting no preserved physical structure (Fig. 2.20A). Structure in most of the coarse member beds is totally obscured by bitumen, but ripple cross-

Figure 2.19. Character of Lithosome C. **(A)** Dense mud dominated IHS. Base of core is to lower left, top to upper right. Coarse member character varies from clean sand beds a few cm thick to flaser interlaminated mud and sand. Note the fairly consistent thickness of the inclined units, and sand filled burrows subtending into several of the mud beds. AA/12-31-96-11 W4. **(B)** Upward muddying inclined units with typically sharp, erosive bases. Note the presence of synaeresis cracks at the top of some units, indicating an increase in water salinity associated with the transition from fine to coarse member deposition. AA/04-06-97-12 W4, 165.8 m. **(C)** Deformation of interlaminated mud and silt/sand. AA/12-31-96-11 W4, 89.2 m. **(D)** Churned base of a slump deposit found near the base of a succession. Note the chaotic mixture of mud with coarser material, including quartzose pebbles, the "drag folding" of laminae at the base, and the infiltration of fluidized mud into the underlying sand. AA/16-36-96-12 W4, 109.8 m.


op Core #24 76.96 m
Bottom 76.96
A
synaeresis crack
B
C
quartzose granules
mud infiltration
D

lamination on a 0.5 – 2 cm scale is locally apparent.

Burrowing in the coarse members consists of an assemblage dominated by *Planolites* and *Teichichnus*, with *Cylindrichnus*, *Chondrites* and indistinct compound burrowing also present in some examples. Burrowing is concentrated on interlaminated mud and silt/sand, with *Teichichnus* tending to be less abundant where sands are thicker and cleaner (Fig. 2.20B, C). Consistency of burrowing between successive coarse members in often quite low, and intensity of burrowing varies significantly between example successions.

The fine members of this IHS species are composed of superficially structureless mud. While in some cases the mud is indeed structureless, in most instances subtle sub-mm- to cm-scale lamination is present in the form of diffuse to locally crisp variation in grain size and content of granular material. The content of silt/sand in these muds varies from undetectable with the naked eye to local examples where the "mud" is in truth grain supported silt/sand impregnated with clay (Fig. 2.20D). Locally, sand found in the fine members appears coarser than that found in the adjacent coarse members (Fig. 2.21A, B). In places, carbonaceous detritus makes up a significant portion of fine member deposits in horizons of mm- to cm-scale (Fig. 2.21C).

Bioturbation of the fine members is dominated by *Planolites* with rare *Teichichnus* and indistinct compound reworking. Intensity of burrowing within the mud varies from rare to locally high, with a general direct relationship between silt/sand content and degree of reworking. Burrowing is often concentrated on the tops of dense mud beds, indicating colonization of the consolidated mud surface during a hiatus between mud and sand deposition. Locally, burrowing of sand-rich muds imparts a Swiss cheese-like appearance.

The contacts between coarse and fine members may be gradational, sharp or burrow obscured. In general, the transition from sandy to muddy deposition is more gradational than the transition from muddy to sandy deposition, although some sharp-

Figure 2.20. Character of Lithosome C. **(A)** Poorly developed "coarse members" consisting of burrow-worked sandy horizons in the mud. AA/16-36-96-12 W4, 104.9 m. **(B)** Bioturbated, poorly developed coarse members. AA/12-31-96-11 W4, 82.9 m. **(C)** Localized burrowing within sandy horizons, and subtending into the underlying dense mud. AA/12-31-96-11 W4, 68.2 m. **(D)** Highly burrowed sandy mud. Much of the "mud" is actually grain supported sand impregnated with mud. AB/05-29-96-12 W4, 135.4 m.

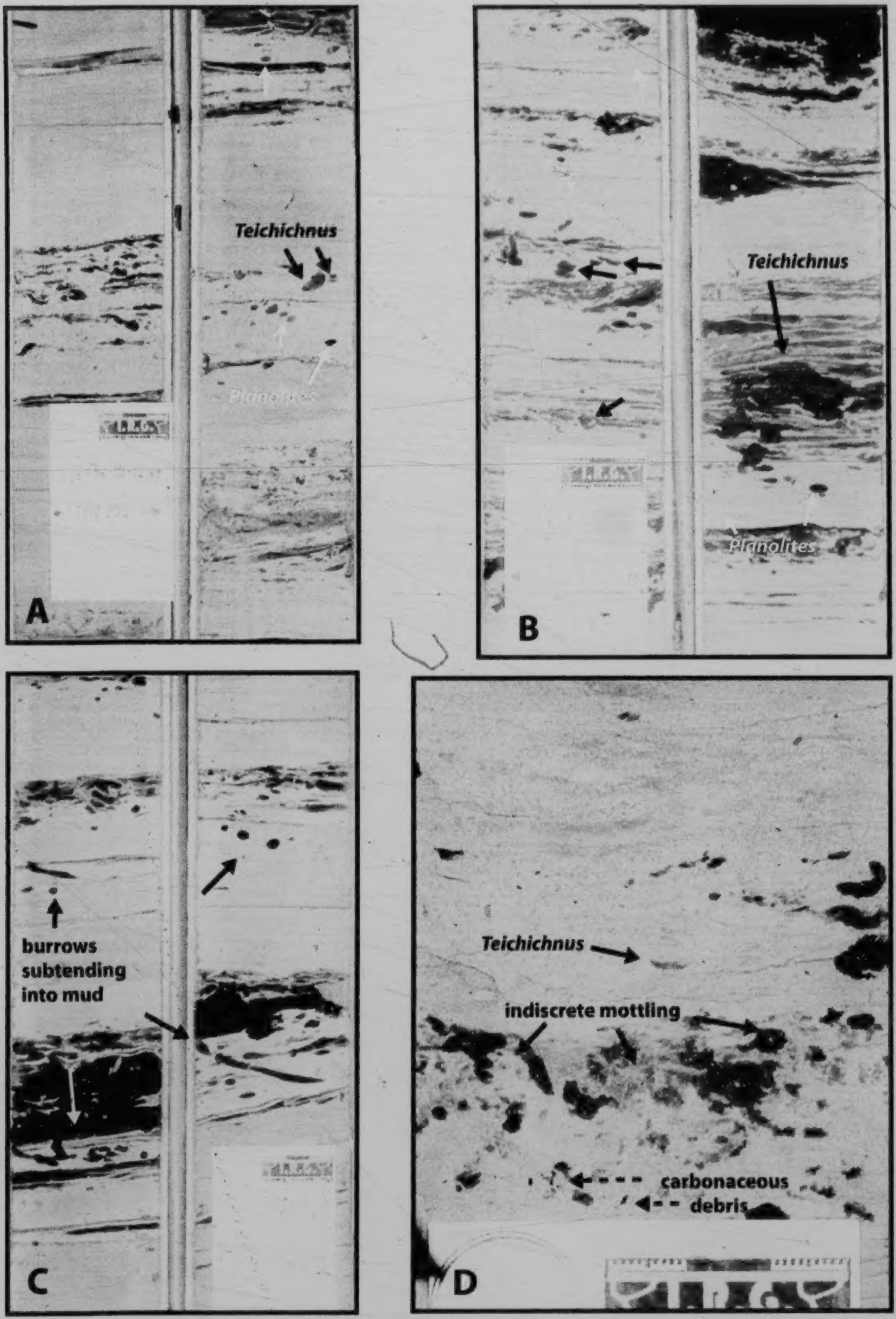
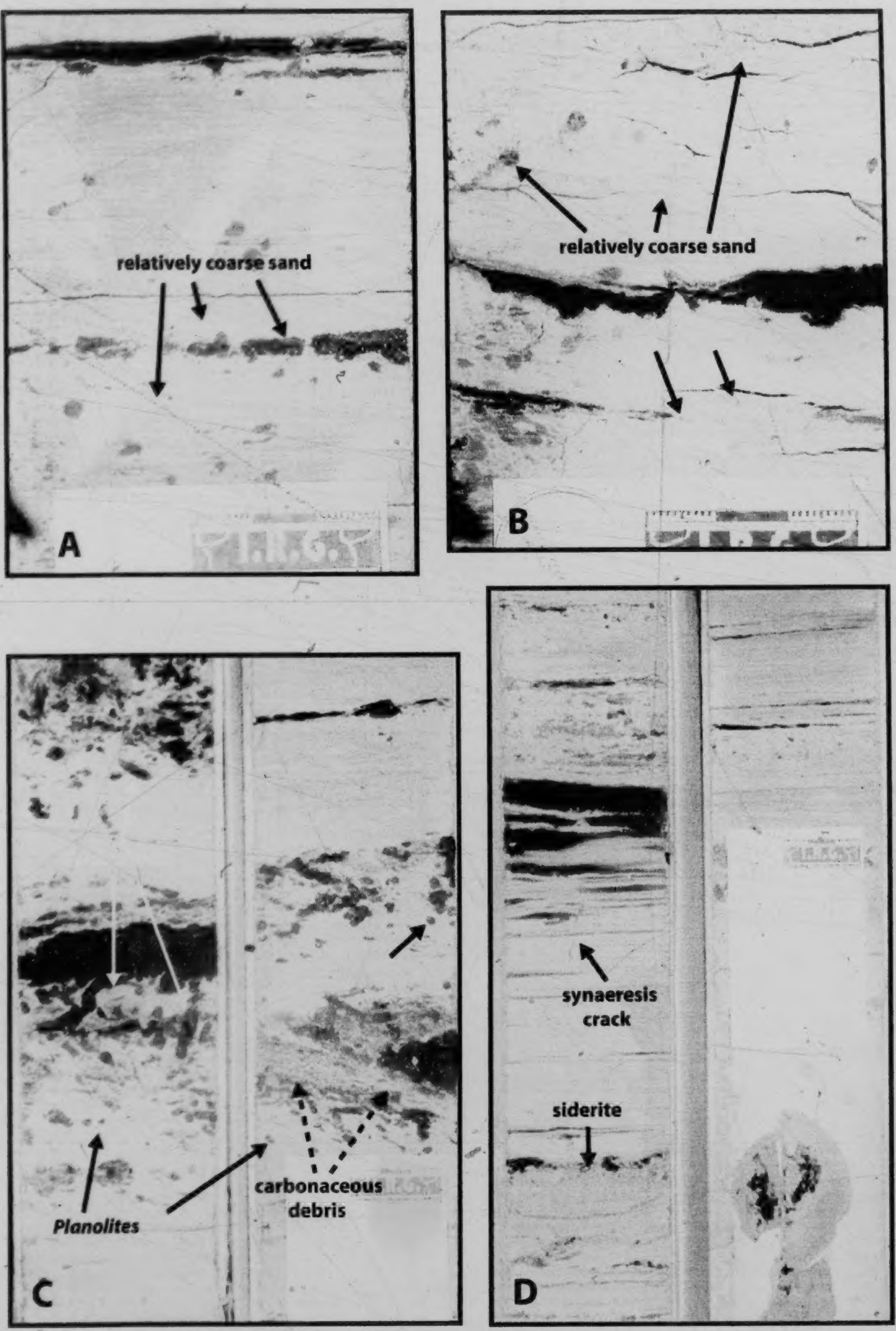

Teichichnus
Planolites
A
Teichichnus
Planolites
B
burrows
subtending
into mud
C
Teichichnus
indiscrete mottling
carbonaceous
debris
D

Figure 2.21. Character of Lithosome C. **(A, B)** Fine member material containing relatively coarse sand. The sand occurs in discrete lenses and laminae, as well as distributed within burrow worked horizons, and is notably coarser than the sand within associated coarse members. This implies that the fine member deposition was associated with relatively energetic periods of flow and a sediment load that was coarser, and less well sorted than that associated with coarse member deposition. AB/04-11-96-12 W4, (A) 99.7 m, (B) 99.4 m. **(C)** Highly burrowed mud dominated IHS. While bioturbation is intense in the sandy material, the cores of the dense mud beds remain relatively untouched. Note the concentration of carbonaceous debris above the scale card. AB?05-29-96-12 W4, 136.3 m. **(D)** Synaeresis crack associated with the transition from fine member to coarse member deposition. This indicates that deposition of the fine member mud took place under conditions of suppressed salinity relative to the deposition of coarse member sand. AA/12-15-96-12 W4, 96.0 m.


relatively coarse sand
A
relatively coarse sand
B
Planolites
carbonaceous debris
C
synaeresis crack
siderite
D

based muds are noted. In several instances, synaeresis cracks are seen at the transition between fine and coarse member deposition (Fig. 2.21D).

Within this IHS lithosome successions exhibit consistent fining upwards grain size profiles. Dipmeter data shows that the inclination of the IHS is greatest where coarse members are relatively thick. Inconsistencies within the dipmeter profile over a meter or two are fairly common, and occur most often where the dip reaches or exceeds 8°. These are thought to represent levels at which slump removal of material, and subsequent re-establishment of a stable point bar surface took place.

Observations are consistent with deposition near the seaward limit of turbidity maximum excursion. The deposition of dense, structureless mud is known to take place from the turbidity maximum in modern estuarine systems at times of high fluvial influx, and strong density circulation (Meade, 1972). The observation that maximum grain size in fine members locally exceeds that of coarse members suggests that deposition of the former was associated with increased competence of flow and/or a coarser, less well sorted source of bedload sediment. The occurrence of synaeresis cracks suggest that the fine member muds were deposited under suppressed salinity relative to the coarse member sands. The concentration of bioturbation within and subtending from the coarse members also suggests that conditions were less hospitable during fine member deposition, likely due to a combination low salinity, high turbidity and unstable substrate. The minimal accumulation of coarse member sand may be the result of bed load bypass across a scoured and cohesive, or mud armored substrate during periods of strong tidal flow.

Lithosome D

This lithosome consists of sand dominated IHS exhibiting inconsistent inclined unit thickness, typically sharp coarse-fine member contacts, and relatively abundant burrowing of both fine and coarse members (Fig. 2.22A). Examples successions exceed 30 m in thickness with broadly consistent character and stratal orientation. In addition to occurrences in core, this lithosome also occurs prominently in outcrop along the Athabasca and Steepbank Rivers (Fig. 2.22B). Several subtle internal discontinuities are found in each of these IHS intervals examined, highlighted by inconsistencies in the dipmeter profile, grain size, and abundance of burrowing.

Coarse members range from 5 – 100 cm thick and are composed dominantly of moderately well sorted coarse silt to upper very fine sand. Physical structure within the coarse members is largely obscured through bitumen staining, but parallel lamination and cross-lamination in 1 – 4 cm sets are locally evident through the main body of the IHS. Towards the base of the successions, cross-stratification in sets 5 – 25 cm thick is common (Fig. 2.22C). Locally, the amalgamation of sand beds with little or no intervening fine member deposition is evident.

The coarse members contain a burrow assemblage dominated by inclined *Cylindrichnus* (Fig. 2.23A, B), with lesser amounts of thin *Skolithos* (commonly <1 mm in diameter), and local indistinct mottling. It is doubtful that all biogenic structure in the sands has been recognized, as only that which is expressed through distinct grain size contrast is apparent through the bitumen stain. Burrowing of the coarse members exhibits a broad upward increase in abundace. Mud walled *Cylindrichnus* are often present in sand with no associated mud laminae. Such occurrences may mark concealed bed junctions, where a temporarily deposited mud was subsequently removed, or alternately may reflect mud sequestration from the water column by the burrowing organism.

Fine members vary in thickness from muddy partings a few mm thick to mud-dominated intervals up to 20 cm thick. The character of the fines also varies. Towards the base of the IHS, the fine members commonly consist of structureless mud laminae a few mm to a few cm thick interlaminated with sand (Figs. 2.23C, 2.24A). These structureless muds often contain abundant disseminated granular material as coarse as

Figure 2.22. Character of Lithosome D. **(A)** Sand dominated IHS. Base of core is to lower left, top to upper right. Note the sharp contacts between coarse and fine members, and the inconsistent thickness of the couplets. Burrowing is common in both the coarse and fine members. A prominent horizon of *Cylindrichnus* is found just below 155m. AA/16-06-97-12 W4. **(B)** Sand dominated Lithosome D IHS in outcrop along the Steepbank River Valley. Note the inconsistent thickness of the inclined units, and the local bifurcation of fine member mud beds. **(C)** A robust cross-bed composed of relatively poorly sorted sand found near the base of a succession. AA/08-06-97-12 W4, 167.3 m.

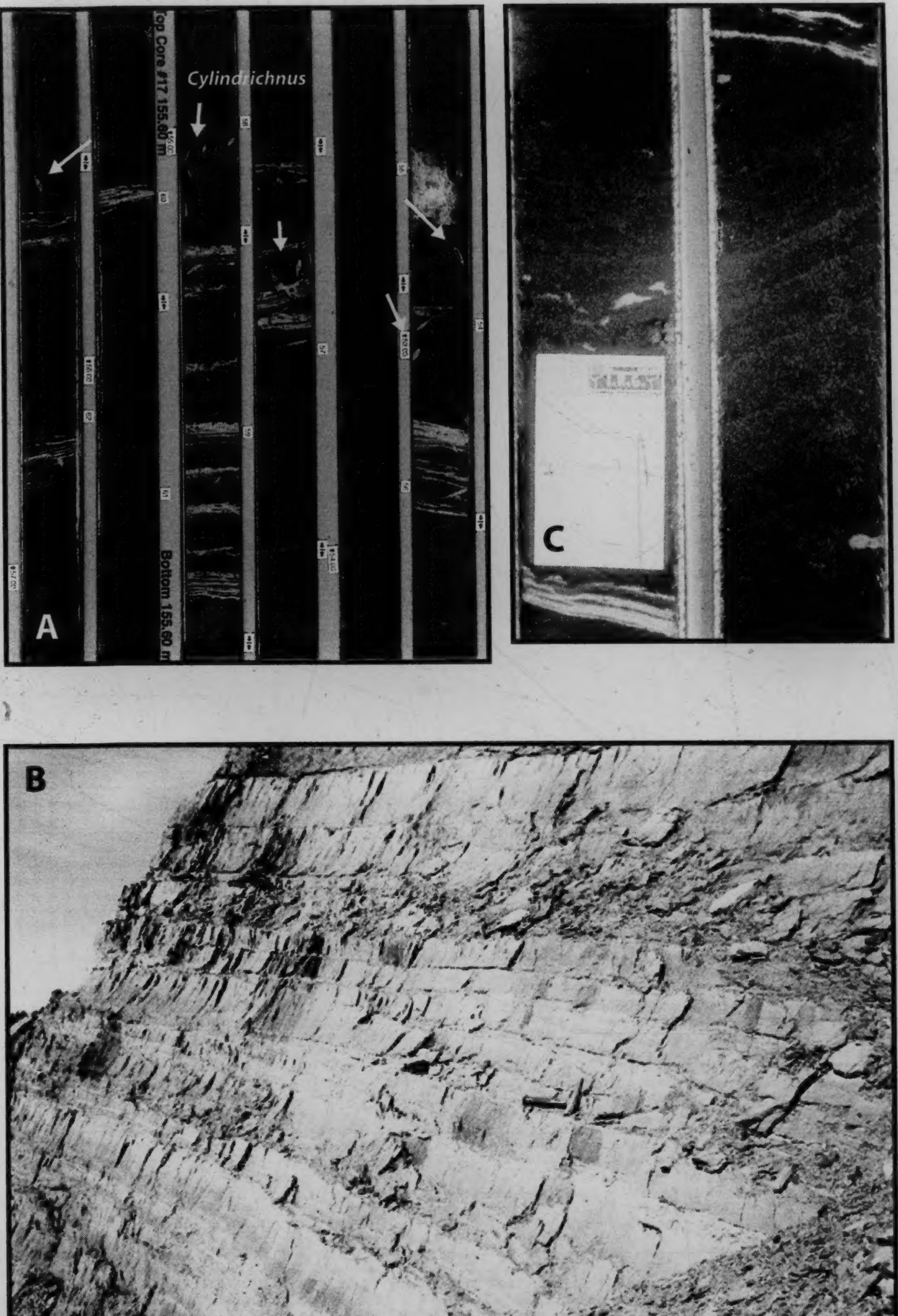

Cylindrichnus
Top Core #17 155.60 m
Bottom 155.60 m
A
C
B

Figure 2.23. Character of Lithosome D. **(A)** Prominent *Cylindrichnus* within the coarse members. While the burrows are lined with mud, many are not associated with preserved mud laminae. This may reflect the erosion of a temporarily deposited mud layer, or mud sequestration from the water column by the trace makers. The fine member material appears to be a combination of coarsely interlaminated mud and silt/sand, and transported mud chips. Burrowing within the fines includes *Planolites* and ?*Chondrites*. AA/16-06-97-12 W4, 155.2 m. **(B)** Mud lined *Cylindrichnus* within the core of a coarse member bed in outcrop. **(C)** Coarsely interbedded dense mud and sand from near the base of a Lithosome D succession. Some of the mud within the sand beds appears to be composed of transported clasts. Note the presence of synaeresis cracks at the top of one mud bed. AA/08-06-97-12 W4, 146.8 m.

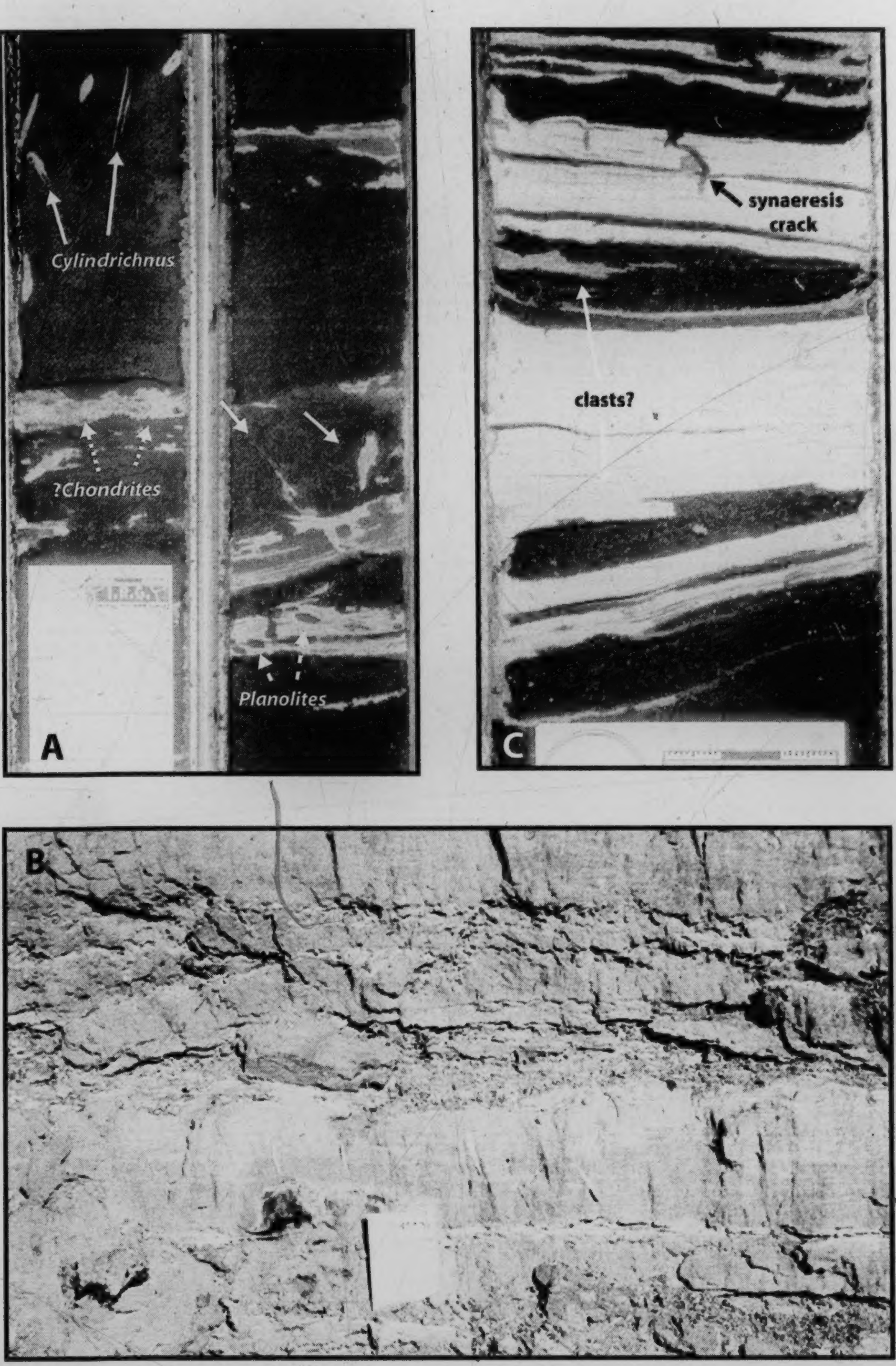
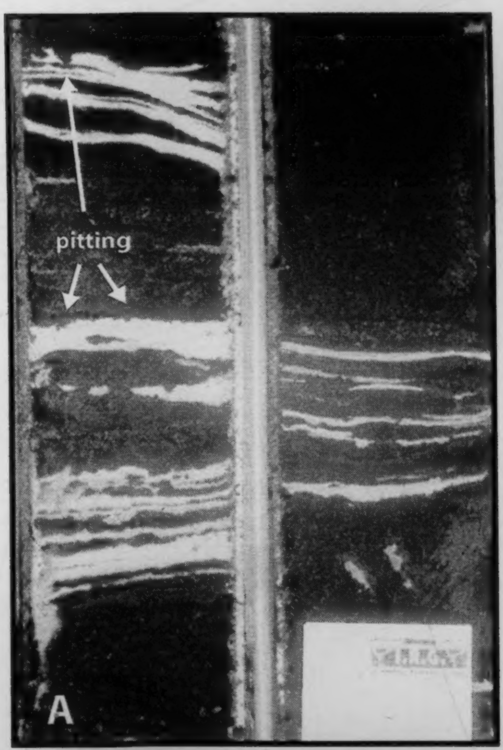
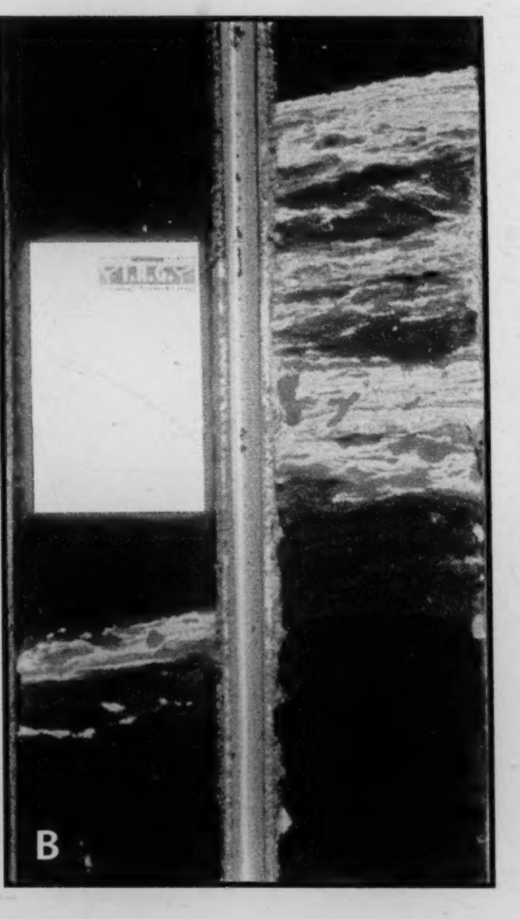
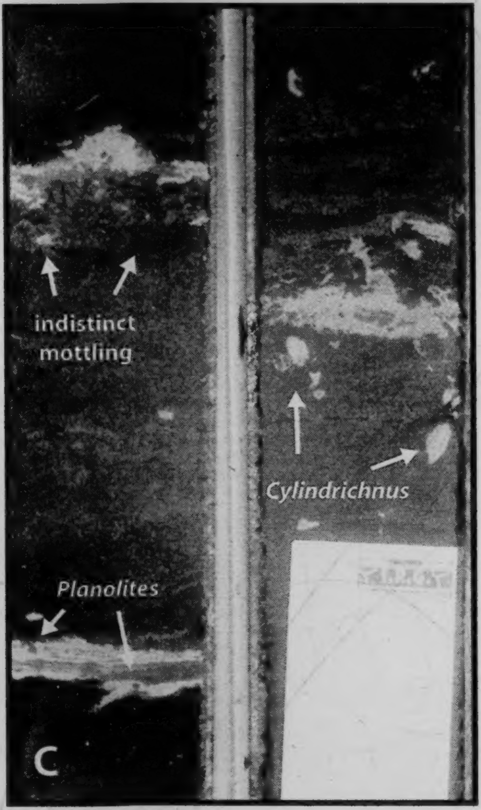

Cylindrichnus
?Chondrites
Planolites
A
synaeresis crack
clasts?
C
B

Figure 2.24. Character of Lithosome D. **(A)** Fine member material composed of coarsely interlaminated mud and sand. The mud has a very fluidy character, suggesting rapid deposition from a high concentration suspension. While no bioturbation is evident within the mud laminae, some epichnial pits and furrows are found along their tops. Photo is taken from near the base of a succession. AA/08-06-97-12 W4, 161.0 m. **(B)** Fine member material composed of finely interlaminated mud and sand. The lenticular interlamination and moderately abundant burrowing suggest deposition took place from a lower concentration suspension, and was influenced by weak tidal flow. AA/16-06-97-12 W4, 152.3 m. **(C)** Burrow obscured fine members. AA/08-06-97-12 W4, 141.4 m.


pitting
A


B


indistinct
mottling
Cylindrichnus
Planolites
C

the accompanying coarse member sediment, and in many instances, a thin rind of mud infiltration into the underlying sand bed is observed. Moving upward from the base of the IHS, fine members take on a more finely laminated character, with mm-scale parallel and lenticular interlamination between mud and silt/sand (Fig. 2.24B). The relative proportions of mud and silt/sand can vary greatly, and in many cases burrowing has obliterated primary structure (Fig. 2.24C). These interlaminated fines contain granular material as coarse as seen in the associated coarse members, and notably lack the crispness of character observed in the interlaminated fines of other IHS lithosomes. Fine carbonaceous debris is locally found within fine members of both structureless and laminated character.

Burrowing within the fine members is dominated by *Planolites* with lesser *Teichichnus*, *Cylindrichnus*, mud-filled *Skolithos*, and compound burrowing. Degree of bioturbation varies considerably between successive fines, with a general trend towards more intense working of thicker fine members.

The contacts between coarse and fine members are typically sharp. The transition from fine to coarse member deposition is erosive, as evidenced by both the characteristically sharp tops of fine members and the locally evident amalgamation of sand beds. Locally, however, an upward coarsening of deposition preceded the erosive onset of the clean coarse member sand deposition.

Intervals of this IHS lithosome display remarkably stable orientation, with a very smooth dipmeter profile. Within each succession, however, several subtle discontinuities are present highlighted by inconsistencies in the abundance of bioturbation and, in some cases, the development of a minor lag. As these discontinuities are commonly developed as sand-on-sand contacts with little in the way of visual cues, they are difficult to identify without careful logging.

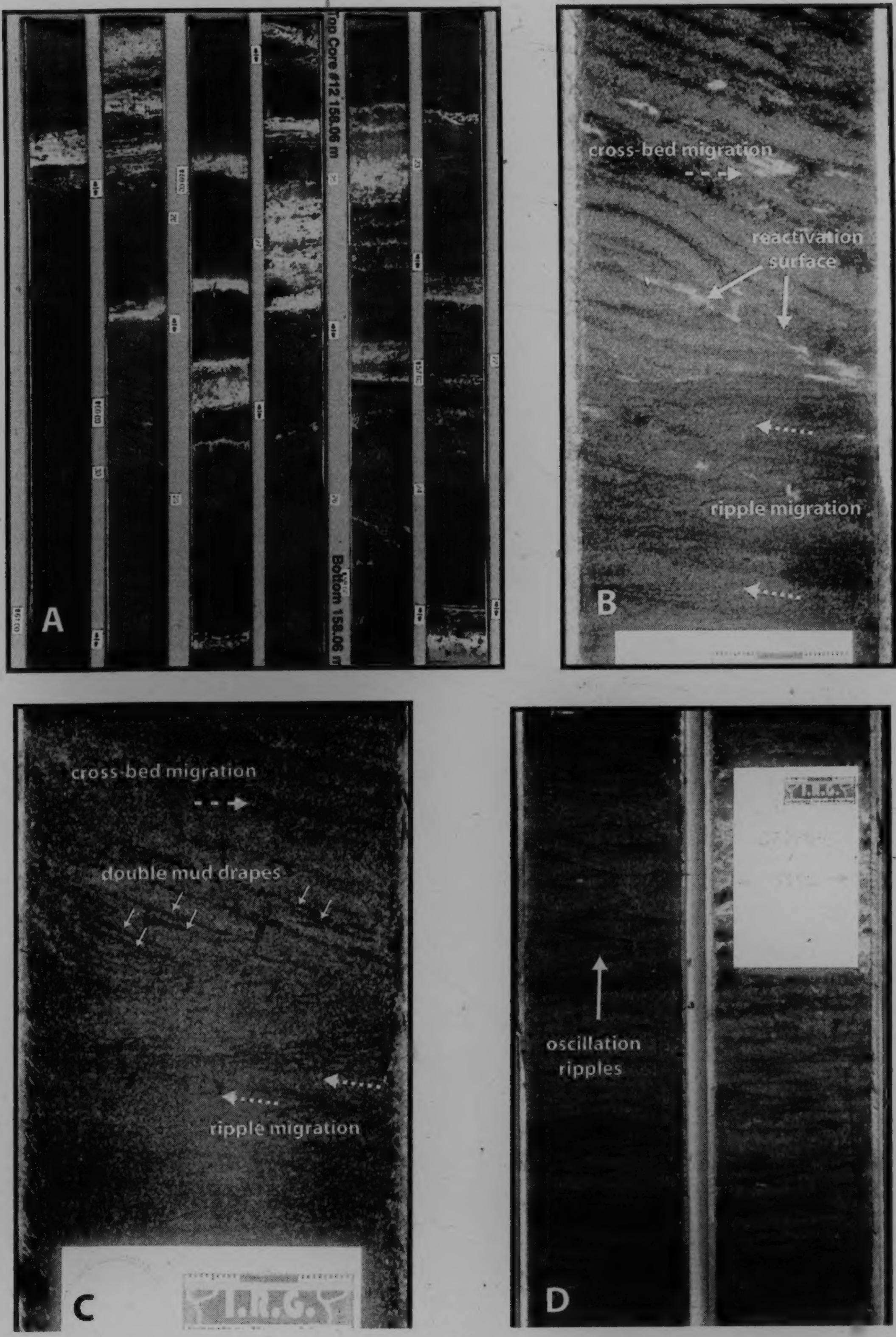
Observations are consistent with deposition at, or slightly seaward of the outer limit of turbidity maximum excursion. The relatively abundant burrowing of both coarse and fine members within this IHS species points to conditions conducive to sediment colonization during the entire IHS depositional cycle. The deposition of well sorted, very fine sands associated with the development of vertical dwelling burrows indicates relatively consistent flow strength, texture of the supplied sediment, and salinity. The intermittent development of poorly laminated fine members may reflect deposition from the periphery of the turbidity maximum, tidal redistribution of muddy sediment or a combination of the two. The collection of a fluid mud phase at the base of estuarine channels through settling of the turbidity maximum during periods of reduced current has been documented and discussed in several papers (Meade, 1972, Allen et al., 1980, Einstein and Krone, 1962). The trend towards fluidy, structureless muds near the base of these successions suggests that this process was important, and at times, this portion of the channel system contained highly turbid waters. The disseminated silt/sand present within many of the structureless mud layers may have settled to the channel base with clays, or may represent material which was deposited on top of a recently accumulated mud layer lacking the competency required to support it (Terwindt and Breusers, 1972).

The similarity of maximum grain size present within coarse and fine members points to comparable competency of flow during their deposition. This would suggest that the heterogeneity of sediment character resulted from variable suspended sediment supply as much as or more so than variation in flow strength.

Lithosome E

This lithosome consists of sand dominated IHS with a coupled muddying and coarsening upward trend. The coarse member sands contain numerous characteristics indicative of tide-dominated deposition (Fig. 2.25A). Moderate to high abundance burrowing with relatively high diversity is present within both coarse and fine members, and is locally seen to cross between them. While this succession exhibits fairly unstable

Figure 2.25. Character of Lithosome E. All from AA/07-23-96-13 W4. **(A)** Interbedded cross-stratified sand and highly burrowed mud. Base of the core is to the lower left, top to the upper right. Note that while the contacts between coarse and fine members are typically sharp, bioturbation commonly crosses the contacts. **(B)** Opposing cross-bed and aggradational ripple cross-lamination. The cross-bed contains rhythmic striping with respect to mud chip content and a reactivation surface, both of which are indicative of tidal rhythmicity of flow. The opposition of bedform migration may have resulted from unequal flood and ebb tidal flow, or flow separation over the crest of the larger bedform, and backflow within its trough. 60.1 m. **(C)** Double mud drapes at the base of a cross-bed, indicating inequalitiy of flood and ebb tidal flow. Again, the opposition of bedfrom migration between the cross-bed and underlying aggradational ripple cross-lamination is seen. 161.0 m. **(D)** Oscillatory wave ripples. Present near the top of the succession, these ripples indicate that wave action exerted some influence on the shallow portions of the shoal. 153.8 m.



A
op Core #12 158.06 m
Bottom 158.06 m
B
cross-bed migration
reactivation surface
ripple migration
C
cross-bed migration
double mud drapes
ripple migration
D
oscillation ripples

stratal orientation, no clear discontinuities are seen within its 17 m thickness.

The coarse members are composed of lower very fine to lower fine sand in beds ranging from a few cm to 1 m in thickness, displaying a slight coarsening upwards trend through the succession. These sands are organized into both ripple cross-lamination sets on the order of 1 cm thick and cross-bed sets typically less than 15 cm thick. The cross-beds commonly display rhythmic grain size striping (Fig. 2.25B), and locally contain double mud drapes in their toesets (Fig. 2.25C). Near the base of the succession, cross-bedding in sets up to 40 cm thick is evident. Locally, cross-beds and fine ripple cross-laminae are seen in an immediately superjacent relationship, with opposing migration direction. This situation may have been generated either through flow reversal, or flow separation over large bedforms in unidirectional flow. Near the top of the succession, oscillatory wave ripples are seen (Fig. 2.25D).

The coarse members exhibit a somewhat inconsistent burrowing character. In some locations (particularly within cross-beds), discrete *Skolithos*, *Cylindrichnus* and (bivalve?) fugichnia are seen (Fig. 2.26A), while in other places, the sand has been highly reworked, leaving a mottled texture with few discrete structures (some *Palaeophycus*) (Fig. 2.26B).

The fine members range from <1 cm to 10 cm in thickness, and vary in character from mm-scale interlamination of mud and sand to structureless mud containing notable disseminated sand. Most of the fine members, however, have been thoroughly burrowed, obscuring primary character (Fig. 2.26C). Within the lower half of the succession, the fine members tend to occur in pairs, with a sand bed 1-5 cm thick separating them (Figs. 2.26D, 2.27A). Carbonaceous debris locally composes a minor portion of the fine member material (Fig. 2.27B).

The fines are typically well burrowed, with the burrowed texture often extending beyond their boundaries into the subjacent and superjacent sand. Discrete burrows in the fines are dominated by *Planolites*, with *Chondrites*, *Teichichnus* and *Thalassinoides* also

Figure 2.26. Character of Lithosome E. All from AA/07-23-96-13 W4. **(A)** Highly burrowed Lithosome E IHS. The high abundance of burrowing has totally obscured the primary character of the muds, and locally the sands. Burrowing in the muddy sediment is quite indistinct, with *Planolites* and *Chondrites* comprising the only clear forms. Biogenic structure in the sand varies from indistinct mottling immediately above and below the muds (?*Palaeophycus*), to clear vertical dwelling and escape structures within cross-bedded sand. *Cylindrichnus* and *Skolithos* are found above the scale card, and fugichnia (bivalve?) are found to the left. Note the remnant planar lamination found between the two mud layers above the scale card. 157.2 m. **(B)** Burrowing of muddy material. *Planolites* is common in all the fine member material and *Chondrites* is present locally. To the left of the scale card *Palaeophycus* is found in a sandy horizon. The tops of several mud layers are pitted and scalloped. 159.8 m. **(C)** Intense mottling of both coarse and fine member material. Fine lined *Skolithos* and *Palaeophycus* are common in the sand, while few discrete structures are present in the mud. 158.7 m. **(D)** Sand dominated IHS with inconsistent coarse member thickness from near the base of the succession. Base of the core is to the lower left, top to the upper right. At this level, the fine member muds typically occur in pairs. Detail is shown in Figures 2.27A and B.

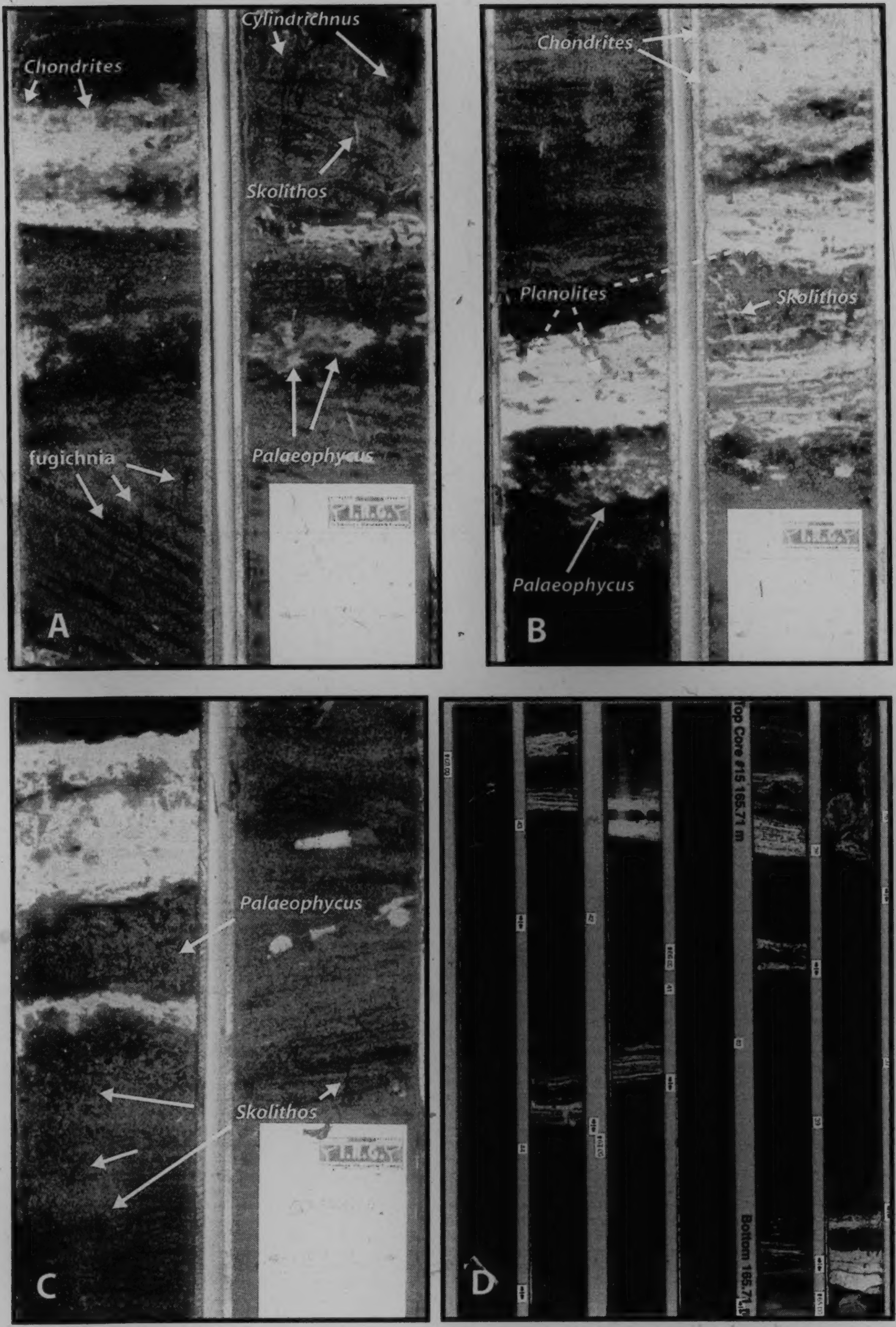
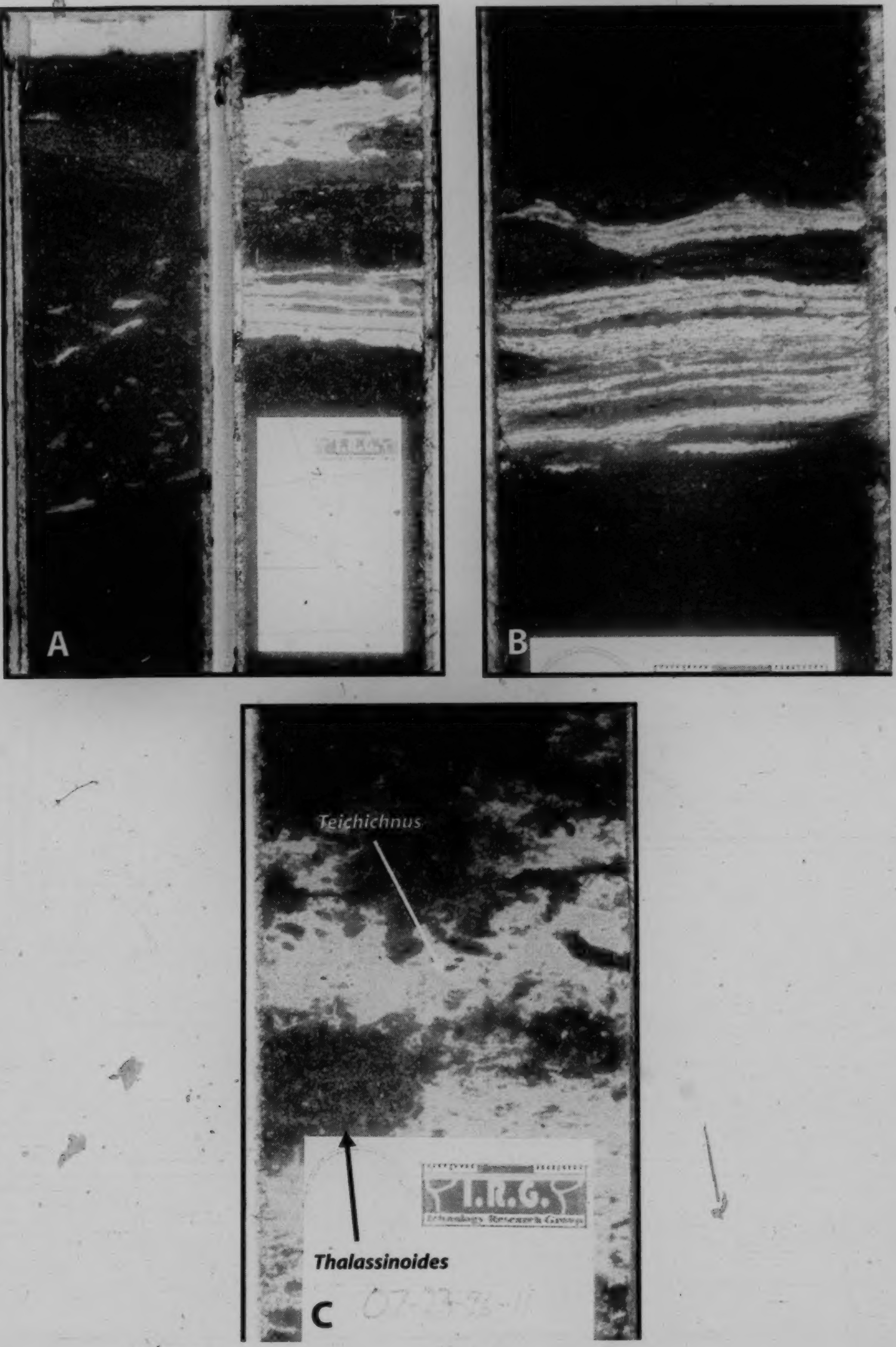

Cylindrichnus
Chondrites
Skolithos
Palaeophycus
fugichnia
A
Chondrites
Planolites
Skolithos
Palaeophycus
B
Palaeophycus
Skolithos
C
Top Core #15 165.71 m
Bottom 165.71
D

Figure 2.27. Character of Lithosome E. All from AA/07-23-96-13 W4. **(A)** Paired fine member mud beds and common mud chips within coarse member sands. 167.4 m. **(B)** Interlaminated "fine member" composed largely of fine mud chips and carbonaceous debris. 167.0 m. **(C)** Burrowing of muddy material. *Planolites* and *Chondrites* are common, and a single clear *Teichichnus* is seen. Much of the bioturbation consists of indiscrete structures. The concentration of sand immediately above the penny is interpreted to be a reworked *Thalassinoides*. 154.3 m.


A
B
Teichichnus
Thalassinoides
C
I.R.G.
Ichnology Research Group
07-27-93-11

present (Fig. 2.27C). The tops of many mud layers contain epichnial pits and furrows, representing colonization and/or grazing of the mud surface.

Contacts between coarse and fine members are sharp and commonly distorted by burrowing.

A clear coarsening upward trend is seen with respect to the maximum grain size present in the coarse member sands. A general upwards decline in the scale of cross-stratification is also seen. The proportion and thickness of muddy fine member beds are seen to increase upwards. The abundance of burrowing in both the coarse and fine member material also increases upwards.

Observations are consistent with deposition seaward of the channelized portion of the system as a tidal shoal within the mouth of the estuary. This lithosome displays clear tidal influence, in the form of double mud drapes and grain size striping in cross-beds. Clear wave influence is seen in clean sand beds at the top of the succession. The coarsening upwards trend, coupled with the inconsistent stratal organization evident in dipmeter contrasts with the character common to IHS from a channelized setting.

The high abundance and diversity of burrowing seen in both coarse and fine members suggests an environment that was much less stressed than that associated with other IHS lithosomes. The lack of clear ichnological discontinuity at coarse-fine member contacts suggests that the change in dynamics between sand- and mud-dominated deposition was not associated with environmental change drastic enough to affect the activity of the burrowing organisms.

Coleman and Wright (1978) described the occurrence of analogous tidal shoals in the macrotidal Ord River Estuary of Western Australia. The shoals they described vary in relief from 10-22 m, with tops awash at low tide, and are interpreted to have formed where flood tidal and ebb tidal sediment transport converge.

The commonly paired occurrence of fine member muds is a bit of an enigma. One possible explanation lies in the inequality of full moon and new moon spring tidal ranges. The paired fines may represent two neap tidal mud accumulations separated by a thin new moon spring tidal sand. The thick accumulations of sand present between paired muds may be the result of common erosive removal of deposited muds, or may reflect the bulk of large scale sandy bedforms, with muds accumulating only in the troughs between.

DISCUSSION

CYCLICITY OF HETEROLITHIC CHARACTER

The dominant order of cyclicity within the presented IHS species is interpreted to be annual. While no single, irrefutable piece of evidence exists to back up this interpretation, there is an abundance of circumstantial evidence.

One line of evidence relies on a comparison with modern settings. Studies from modern estuarine systems suggest that the dominant order on which depositional character varies is annual, influenced by seasonal variation in fluvial influx and water circulation (Meade, 1972; Nichols, 1977; Allen et al, 1980; Uncles and Stephens, 1993, and Lesourd et al. 2003). The variation in water circulation and sedimentation reported in these studies is in good agreement with the variation in sedimentological and ichnological character seen within IHS of the McMurray Formation. For example, the character of mud deposits within the various species of IHS vary from finely laminated with tidal character, to those which are composed of dense, structureless mud. This reflects the variable character seen in the turbidity maxima of modern riverine estuaries under differing fluvial inflow. The character of associated fine and coarse members also suggests that the heterogeneity of depositional character is driven by changes in fluvial input and water circulation dynamics. Muds with tidal character are seen with sands displaying fluvial character, and muds with fluidly deposited character are seen with clean, well sorted sands suggestive of tidal deposition.

Fortnightly and diurnal tidal signature are commonly observed subordinate to the main order of cyclicity. This demonstrates that the main dynamics of heterogeneity took place with a lower frequency. Patterns of bioturbation also point away from a tidal periodicity for the IHS. The distinctly different patterns of colonization typical of fine and coarse member deposition indicate that each took place over a period sufficiently long as to allow for colonization and exploitation by contrasting groups of organisms. If the periodicity were fortnightly tidal, only 7 days would be available for the colonization of each member. This period would be too short to have allowed for the formation of distinct coarse member and fine member communities. Were inclined unit development to take place on a fortnightly time scale, one would expect to see a common alternation of thick and thin units, reflecting the inequality of new moon and full moon spring tides. This has not been observed. The amount of sediment which accumulated in each of the inclined units also indicates that deposition under fortnightly tidal variation is unreasonable. Within Lithosome C, for example, inclined unit thickness of 15 cm and dip of 6° are typical. Using simple trigonometry, this reflects lateral bank accretion of roughly 1.5 m per inclined unit. Channel migration of 1.5 m on an annual basis seems intuitively reasonable. If inclined unit development took place on a fortnightly cycle, however, this would reflect an annual channel migration of approximately 36 m.

While the dominant order of cyclicity is taken to be annual, inter-annual variation is also likely to have played a role in driving heterogeneity. Low recurrence storm events and variation in the dynamics of annual fluvial discharge are two examples of processes which may drive inequality of annual deposition. Inter-annual cyclicity would likely play a major role at the ends of the system, where fluvial and marine influence are most strongly expressed, leading to the amalgamation of high energy inclined unit components (Knishern and Kuehl, 2003). Towards the center of the system, however, the buffering effect of estuarine circulation would have tended to filter out much of this influence.

VARIATION IN CHARACTER ALONG A CONCEPTUAL RIVERINE ESTUARY

IHS from the McMurray Formation display substantial, but structured, variability with respect to lithic and ichnologic character. The sedimentologic character of the IHS lithosomes show clear organization with respect to fluvial and tidal influence. Additionally, the occurrence and morphology of ichnofossils reflect systematic spatial and temporal variation in salinity and turbidity stress. By integrating sedimentologic and ichnologic lines of reasoning, the character of these IHS lithosomes can be resolved into a fluvial to marine gradient.

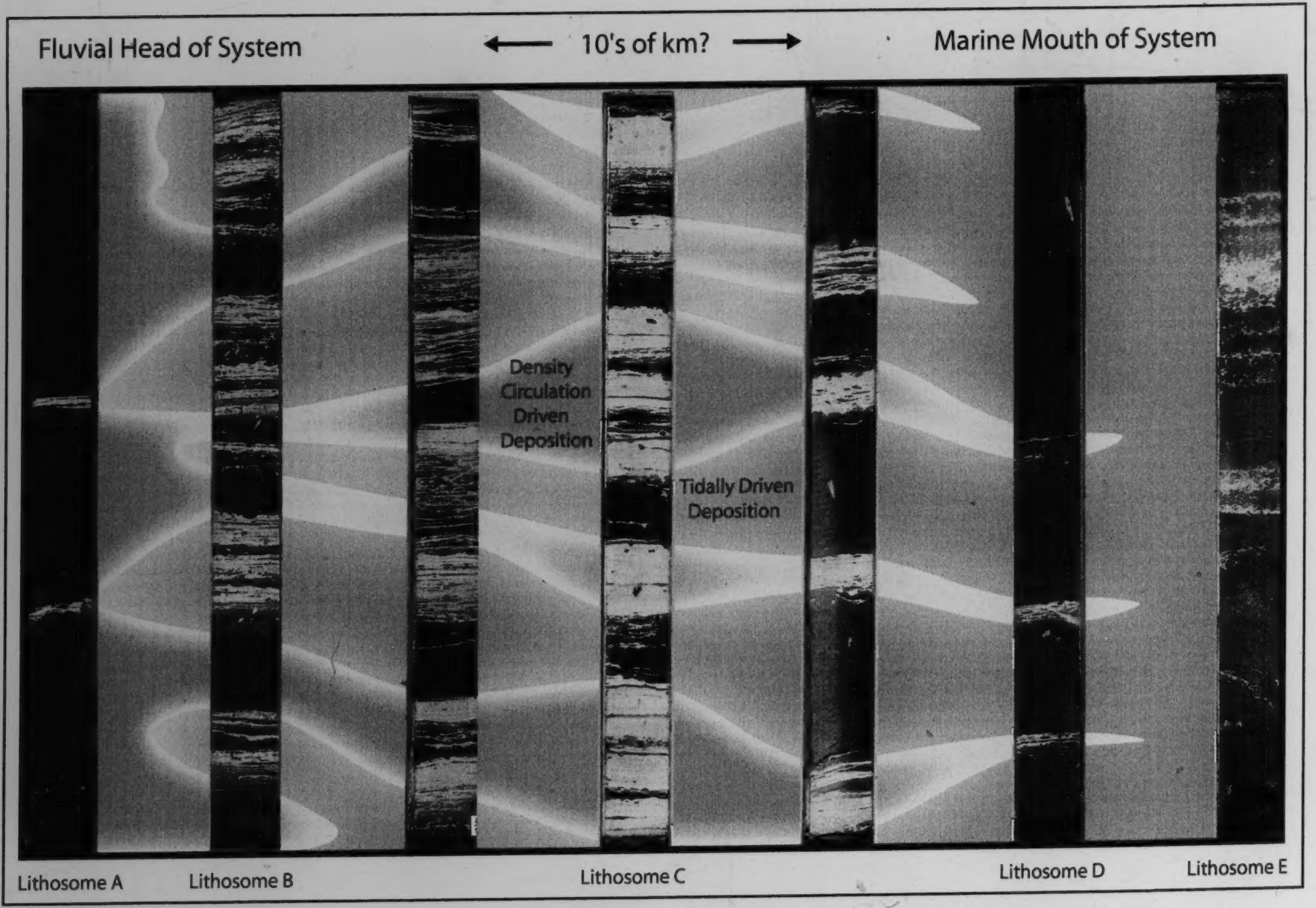
The 5 lithosomes of IHS presented fit into such a gradient, and have been presented in a landward to basinward order. A summary of the character of each lithosome is presented in Table 2.3, and Figure 2.28 illustrates the spatio-temporal relationship in deposition between them. The lithosomes have been arranged in a conceptual system, and do not reflect a single system that has been stratigraphically correlated. Such an exercise would be extremely difficult given the stratigraphic complexity of the McMurray Formation, and is beyond the scope of this study. Additionally, this model is not intended to encompass all variants of IHS seen within the McMurray Formation, as many are interpreted to have accumulated in positions outside of the main riverine channel of the estuarine system (more on this subsequenctly).

In this model IHS character falls into a broadly tripartite distribution, with a sand-dominated seaward flux in the upper reach, a muddy zone of convergent flux in the middle reach, and sand-dominated landward flux in the lower reach. This tripartite distribution reflects superimposed fluvial and tidal energy gradients that decay in opposing directions. The sand dominated IHS deposits from each end of the system contrast strongly in terms of texture, structure, biogenic signature, and stratal organization. Similarly, fine members from the central portion of the system exhibit a

	Lithosome A	Lithosome B	Lithosome C	Lithosome D	Lithosome E
Coarse Member Character	poorly sorted vfL-fL sizable cross-beds throughout	moderately sorted silt-fL texture inconsistent between beds 1 - 3 cm cross-lamination	well sorted silt-vfU fine interlaminated to rare clean sand	well sorted silt-vfU clean, ripple cross-laminated	mod. to well sorted vfL-fL tidal x-beds and ripple x-lamination oscil. ripples near top
Fine Member Character	inconsistently developed starved for silt/sand local tidal cyclicity	lenticular interlamination of mud and silt/sand tidal cyclicity and mud doublets common	dense to parallel laminated silty mud local fine sand	thin dense silty mud layers and coarsely interlaminated mud and silt/sand	coarsely interlaminated mud and silt/sand typically highly burrow reworked
Coarse Member Ichnology	devoid of evident burrowing	rare indistinct mottling some muddy burrows and *Palaeophycus* subtending from fines	variable abundance *Planolites* & *Teichichnus* lesser *Cylindrichnus* and *Chondrites*	moderate abundance *Cylindrichnus*, *Skolithos* and indistinct mottling	low to high abundance *Skolithos*, *Cylindrichnus*, *Palaeophycus*, fugichnia and indistinct mottling
Fine Member Ichnology	rare *Planolites*	moderate abundance *Planolites* dominant	variable abundance *Planolites* dominant often concentrated on mud tops	moderate abundance *Planotlites* with lesser *Teichichnus*, *Cylindrichnus*, and *Skolithos*	low to high abundance *Planolites*, *Chondrites*, *Teichichnus*, *Thalassinoides* & epicnial pits & furrows
Thickness and Consistency of Couplets	5 - 100 cm very inconsistent	10 - 20 cm fairly consistent	5 - 20 cm very consistent in a given set	5 - 100 cm very inconsistent	5 - 100 cm very inconsistent
Stability of Strata Organisation	very unstable	direction stable inclination somewhat variable	smooth, gradual changes punctuated by small inconsistencies - slumps?	very stable	very unstable, particularly at base of succession
Relative Abundance of Coarse and Fine Member Material	strongly dominated by coarse member material	upward change from coarse to fine member dominated in each set	moderately to strongly dominated by fine member material	strongly dominated by coarse member material	dominated by coarse member material, upward increase in fines

Table 2.3. Comparison of the character observed in each of the IHS lithosomes.

Figure 2.28. Diagramatic representation of the spatio-temporal link of depositional style within the riverine estuary. Red regions link depositional character associated with high river discharge and strong density circulation. Blue regions link depositional character associated with low river discharge, and strong tidal circulation. During periods of high river discharge, the head of the system experiences coarse member deposition characterized by poorly sorted, fluvially sourced sand, and a paucity of bioturbation. Towards the mouth of the system, deposition of fines from a high concentration turbidity maximum takes place. During periods of low flow, the head of the system experiences deposition of fines from a tidally maintained turbidity maximum, associated with rapidly fluctuating salinity, and low diversity, largely endogenic burrowing. Towards the mouth, coarse member deposition takes place under the influence of strong tidal currents. Relatively high and stable salinity allows the colonization of the sediment by organisms open to the water column, but an unstable substrate and common physical reworking may limit the preservation of related burrows. Note that sedimentation in Lithosome E, interpreted to have been deposited seaward of the channelized system, exhibits no clear relation to the dynamics within the channel.


Fluvial Head of System
← 10's of km? →
Marine Mouth of System
Density Circulation Driven Deposition
Tidally Driven Deposition
Lithosome A
Lithosome B
Lithosome C
Lithosome D
Lithosome E

progression of character from dense mud to finely interlaminated silt/sand and mud in a landward direction.

As this model provides a predictive and interpretive tool, useful in vectoring IHS character within a depositional system, it may prove extremely useful in fleshing out stratigraphic relationships within the McMurray Formation and similar deposits. As such, the model may aid greatly in the exploration for, and exploitation of high grade bitumen reservoirs within the Athabasca Oil Sands.

FIRM GROUND BURROWING

Within Lithosome C, and occurrences transitional into Lithosomes B and D, sharp, scoured contacts between dense mud beds and superjacent sand beds are quite common. Often associated with these contacts are robust, sand filled burrows subtending from the contact into the underlying dense mud (Fig. 2.29). The fact that these burrows display a passive fill derived from the overlying sand, without significant collapse of the burrow structure, indicates that the mud was fairly firm at the time of colonization, and thus able to support an open burrow network. The scouring and colonization of a firm mud substrate implies that there was a hiatal period between deposition of the mud and the subsequent sand, a situation analogous to the development of a *Glossifungites* surface (MacEachern et al., 1992).

The development of such contacts takes place with four stages (Fig. 2.30). First, a dense mud accumulates through deposition from a dense, fairly stable turbidity maximum fed through density circulation. Second, the mud must be firmed, which likely takes place under the influence of both gravity induced compaction and synaeresis driven water removal. This takes place as density circulation drops off and more saline waters move in. Third, any loose mud present at the top of the accumulation is removed through the scouring effects of strengthening tidal flow, presenting a firm mud substrate for colonization. Lastly, bedload sand is reintroduced to the area, extinguishing or displacing

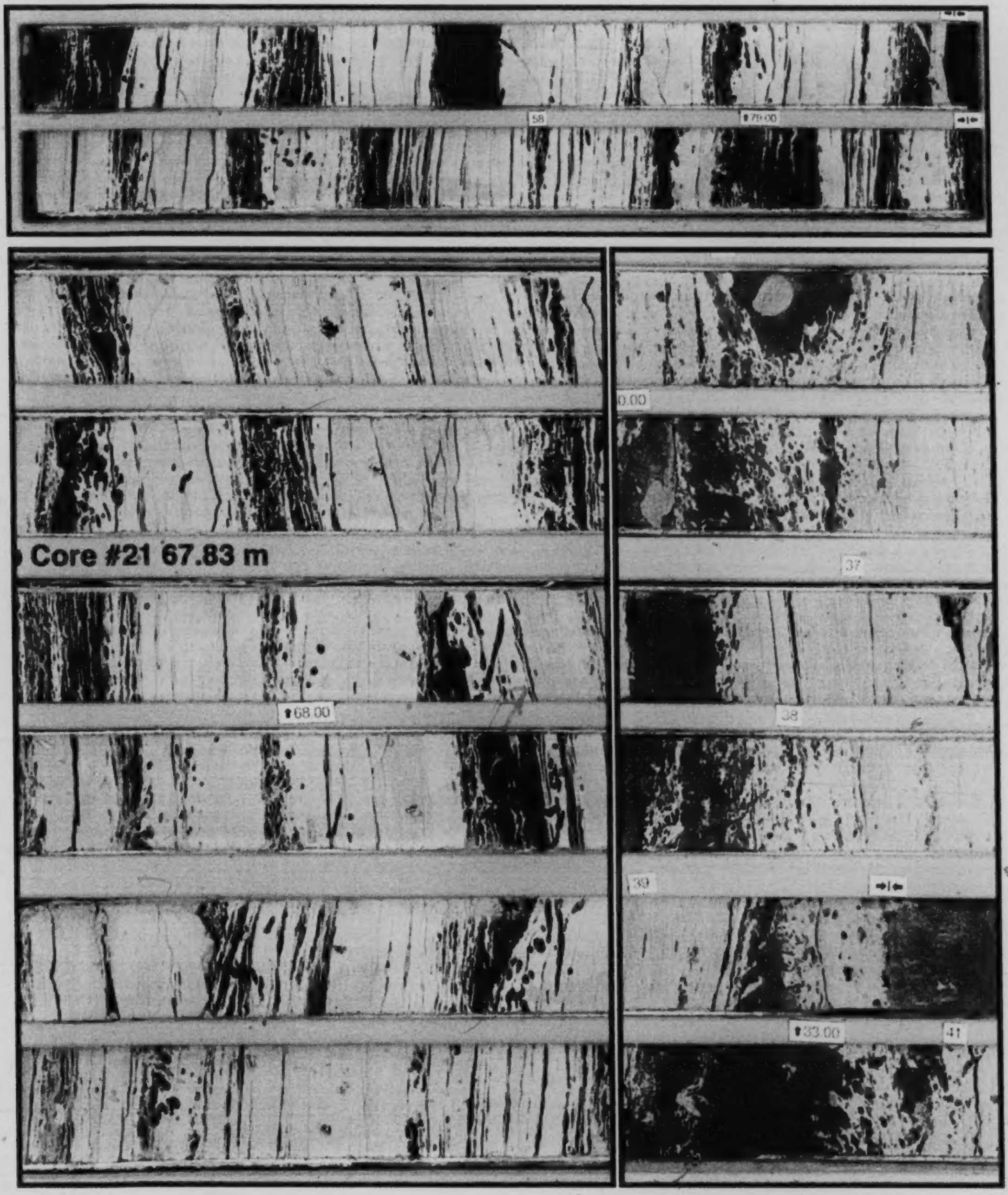


Figure 2.29. Examples of firm ground burrowing penetrating the tops of dense mud units. The presence of a passive sand fill in the burrows indicates that at the time of burrowing, the muds were firm enough to support an open burrow network.

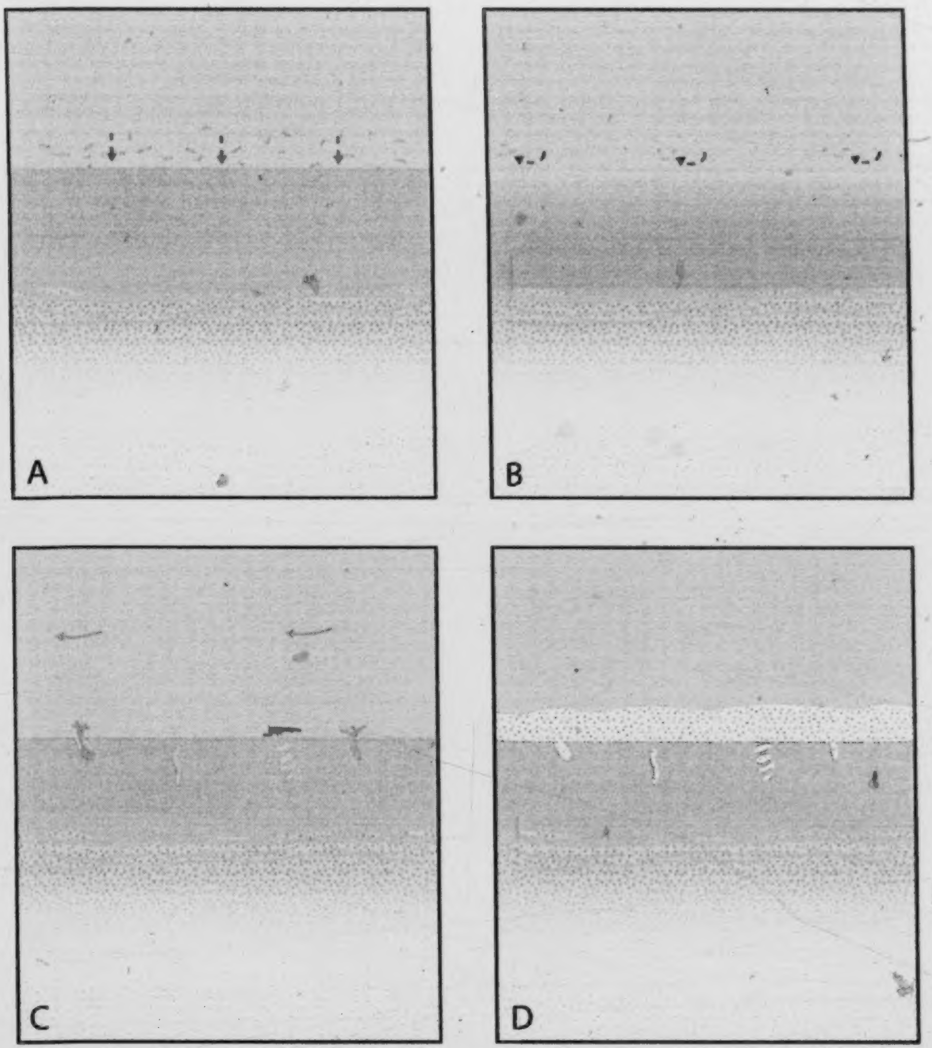


Figure 2.30. Stages in the generation of a firm ground burrow suite. **(A)** Deposition of a dense, fluid mud. **(B)** Scour and deflation of the poorly consolidated surficial layer. **(C)** Colonization of the firm substrate. **(D)** The influx of sand, displacing or killing the burrowing organisms and filling their burrows.

the burrowers, and filling their burrows.

The burrowing requires a hiatal period between the scouring of the mud surface and the onset of sand deposition. This is easily accommodated within the riverine estuary model if one considers the effect of a dense mud blanketing a significant reach of the estuarine channel (Fig. 2.31). As such a layer would blanket both the banks and the base of the channel, no bedload material would be available locally for redistribution as tidal

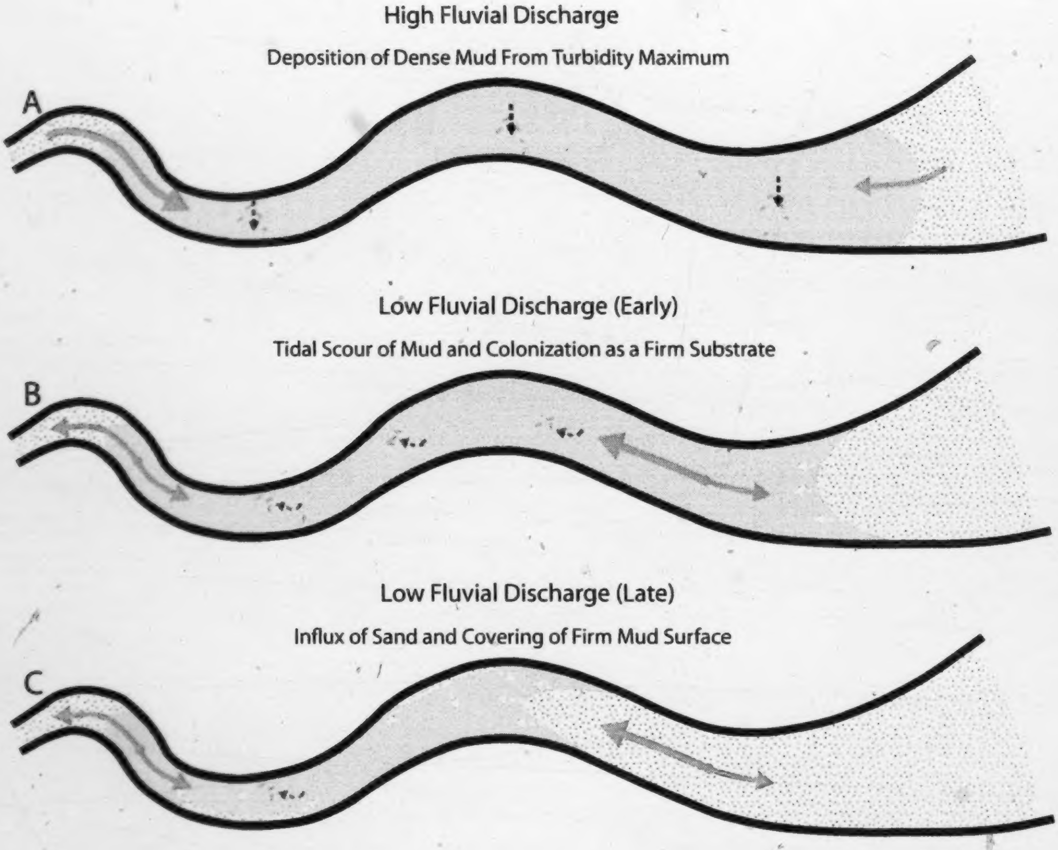

High Fluvial Discharge
Deposition of Dense Mud From Turbidity Maximum
A
Low Fluvial Discharge (Early)
Tidal Scour of Mud and Colonization as a Firm Substrate
B
Low Fluvial Discharge (Late)
Influx of Sand and Covering of Firm Mud Surface
C

Figure 2.31. Stages in the generation of a scoured mud surface in the estuarine channel. **(A)** Deposition of dense mud from the turbidity maximum during high river discharge. This deposition will blanket the entire channel over a certain reach, fixing any bedload material beneath the surface. **(B)** Scouring of the deposited mud by tidally driven flow as river discharge falls off. **(C)** Return to conditions of bedload transport and deposition as coarse material is driven in from the inlet end of the system, and the mud armor on cutbanks is breached.

flow strength increases. The surface of the mud would thus be scoured and left exposed for a significant period until bedload material is either swept in from the marine end of the blanketed area, or the erosive breach of the mud blanket armoring the cutbank yields a local source of sand.

While this situation yields a firm ground burrow suite analogous to the *Glossifungites* ichnofacies, the resulting surfaces are generated on a repeated basis (annually) within an overall depositional, rather than erosive, setting. Additionally, they are of local scope, rather than regional. While these occurrences offer insight into the dynamics of deposition, they have no stratigraphic implication.

FACTORS COMPLICATING THE MODEL

The model presented is intended to deal with the marginal marine, estuarine end of a major continental drainage network, and as such many IHS variants present in the McMurray Formation are extraneous to it. The estuarine environment contains a diverse assortment of tidally influenced channels: main river fed channels, tributary drainage systems which join the main river systems within the tidally influenced realm, tidal creeks feeding and draining tidal flats and subtidal channels in the outer estuary (Fig. 2.32). As tidal creeks and outer estuarine subtidal channels are not directly linked to a fluvial source, they are not subject to the direct effects of variable river discharge. Tributary drainage networks may not exert enough influence over water circulation and sedimentation dynamics within the system to be self-governed in depositional character. Figure 2.33 illustrates how the dynamics of such tributary systems are likely to be overwhelmed by influence from the main fluvial-estuarine system they join.

Additional complexity is added to a universal IHS model through the existence of three distinct sediment provenances during deposition of the McMurray Formation. A large drainage system is interpreted to have fed the basin from the southeast (Christopher, 1980; Ranger and Pemberton 1997), with several smaller drainage networks entering from carbonate highlands to the west and the Precambrian Shield to the east (Fig. 2.34). Systems draining each of these three areas would contrast in size, gradient, volume and flashiness of discharge, the character of their sediment load and water chemistry. As a result, the character of IHS deposited in systems linked to each of the three different source areas is likely to exhibit significant contrast.

STACKING OF IHS PACKAGES

Broadly consistent IHS successions in excess of 30 m thick are reasonably

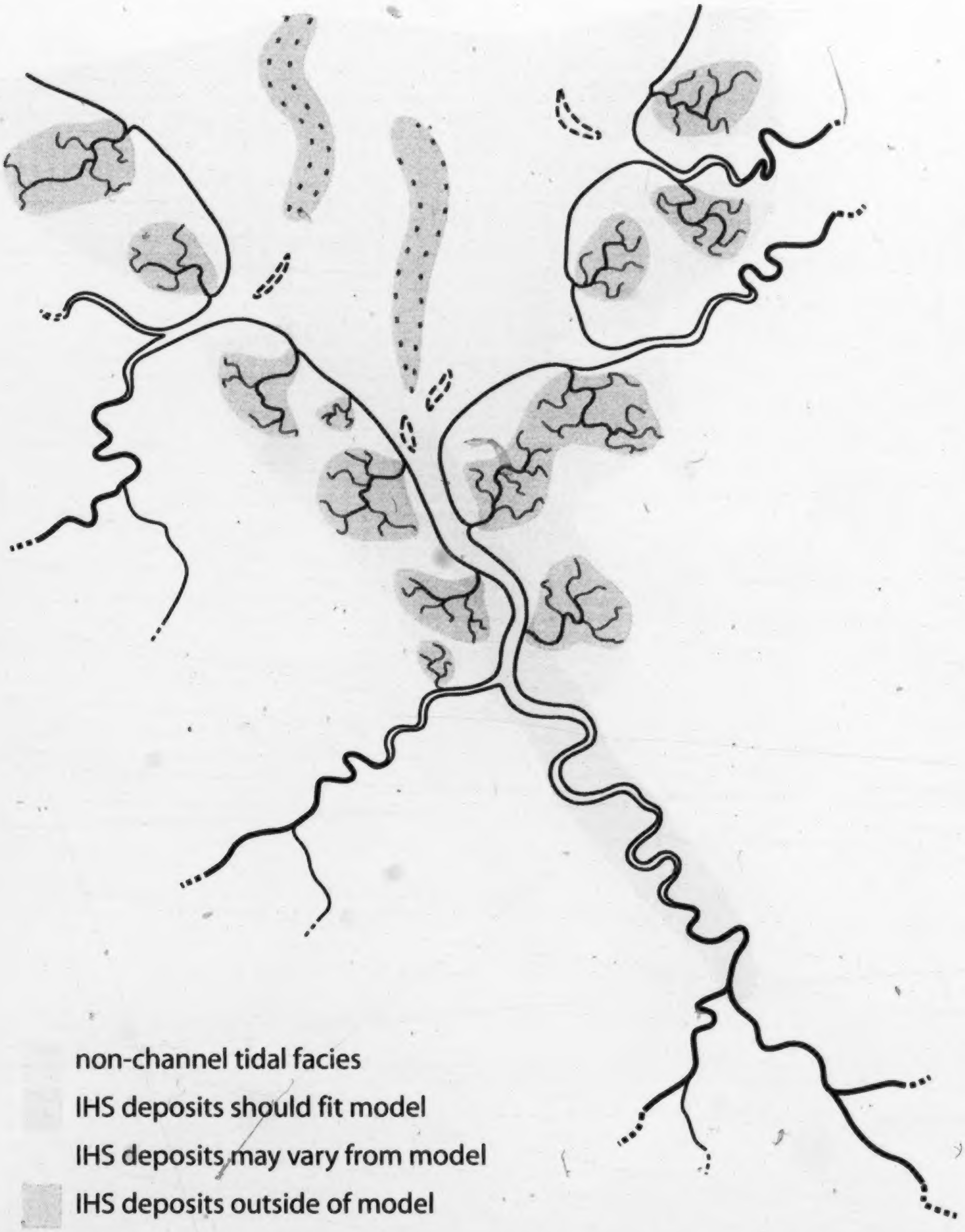
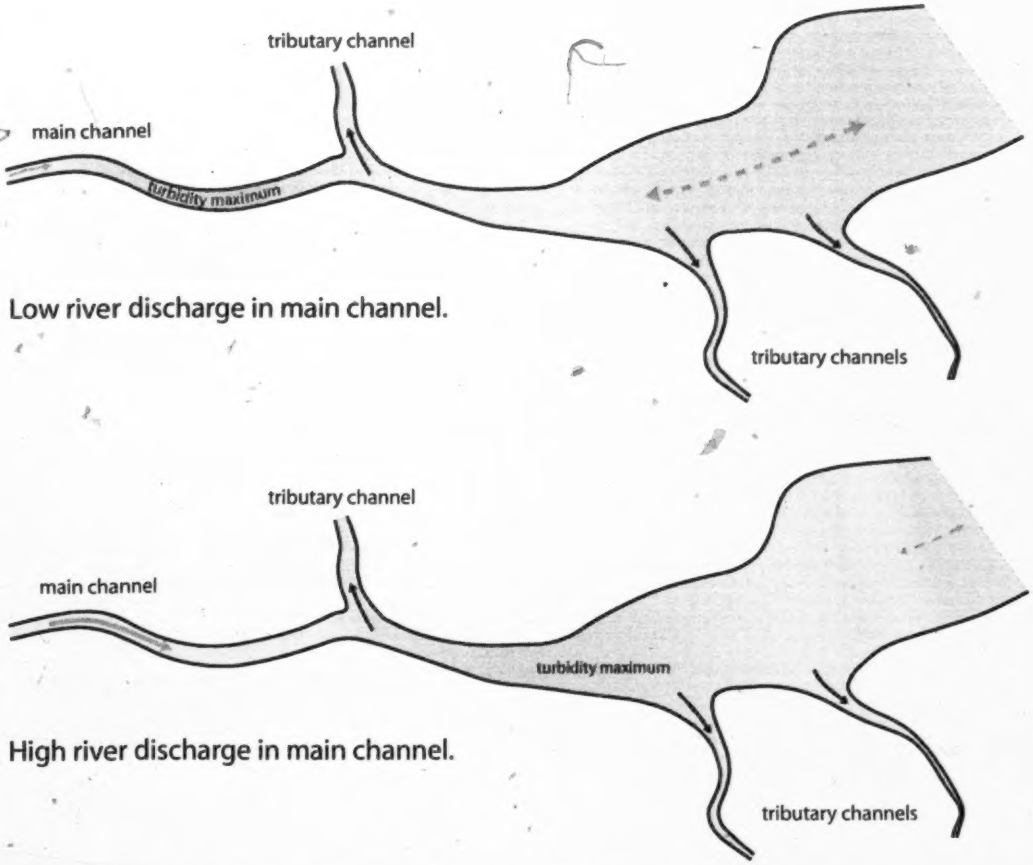

non-channel tidal facies
IHS deposits should fit model
IHS deposits may vary from model
IHS deposits outside of model

Figure 2.32. The relation of various channelized environments within the greater estuarine system to the model presented. The model presented in this paper is intended to address deposition within the main river-fed channel (green). The deposits of tributary drainage systems (yellow) may bear significant resemblance to the model, but will differ owing to several factors. Provenance of the drainage area will lead to variation between systems in the nature of sediment supplied and the dynamics of river discharge. Additionally, circulation and landward directed sediment supply in each of these smaller systems may be influenced by the water circulation effects of the larger system. The deposits of subtidal channels within the estuarine embayment and small tidal creeks draining intertidal flats (red) will bear no resemblance to the model. These two channel types have no connection to continental drainage, and thus are not directly affected by fluvial discharge.



Low river discharge in main channel.

High river discharge in main channel.

Figure 2.33. The overwhelming of tributary channel systems by the main riverine channel. As the dynamics of circulation and sedimentation vary in relation to river discharge through the main channel of the estuarine system, the texture of sediment and chemistry of water available at the mouths of tributary systems varies in concert. This yields a situation in which deposition and biologic activity within the tributary systems are strongly influenced by external factors.

common within the McMurray Formation. The classic interpretation of such successions is that they were deposited as one genetic unit by lateral accretion on the banks of deep channels. Several lines of evidence suggest this interpretation is flawed, however. A review of relevant literature shows that the deposits of modern tidally influenced channels rarely exceed 15 m in thickness. Similarly, other IHS-bearing deposits in the rock record are typically on the order of 5 – 15 m in thickness (Table 3.2). These values contrast significantly with the model of Mossop and Flach (1983), which appeals to the action of 20 – 45 m deep channels in depositing McMurray Formation IHS and the underlying megaripple bedded sands.

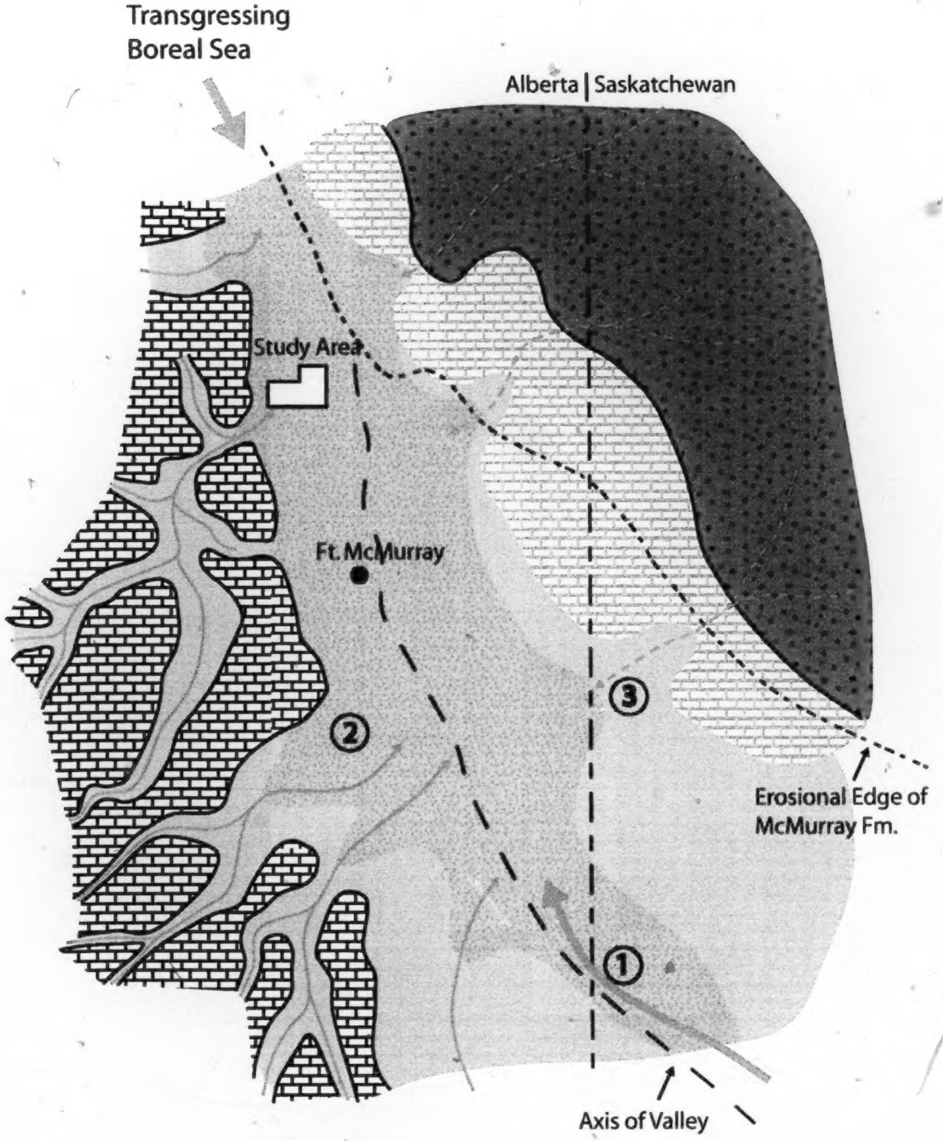


Figure 2.34. Drainage networks from three distinct source areas fed sedimentation within the McMurray Subbasin. **(1)** A large low gradient system draining much of southern and central Saskatchewan. This system would have had damped flashiness of floods, and introduced texturally and mineralogically mature poly-cyclic sediment sourced from Jurassic clastics in Saskatchewan. **(2)** Local, moderate to high gradient systems draining resistant carbonate highlands to the west. These systems would have had flashy floods and been starved for bedload siliciclastic material. **(3)** Local to regional, low to moderate gradient systems draining areas of the Precambrian Shield. These systems would have had flashy floods, and introduced texturally and mineralogically immature sediment.

While thick successions of IHS with broadly consistent character and stratal organization are present in core and featured prominently in several key outcrops, other encountered successions display significantly different character. Many examined successions consist of stacked sets of IHS with consistent orientation, but contrasting sediment character. Other successions are remarkably consistent in sediment character, but contain clear discontinuities across which the orientation of the IHS changes significantly. This implies that the stacking of discrete sets of IHS to form thick successions is the norm. Indeed, when thick successions with consistent sediment character and stratal organization are examined in detail, subtle but significant discontinuities are commonly identified.

The megaripple bedded sands that typically underlie the IHS in outcrop have been classically interpreted as basal deposition from the deep IHS generating channels (Mossop and Flach, 1983), an interpretation which is still applied by some (e.g. Brekke and Evoy, 2004; Strobl et al., 2004). These sands, however, can be shown to have no direct depositional relationship with the IHS. The deep channel model, with its tie between the IHS and the megarippled sands, was based on outcrop (of Lithosome D) along the Athasabasca and Steepbank Rivers. In core, however, examined intervals of Lithosome D display no association with such sands. Indeed, when outcrop along the Athabasca River is examined, a clearly erosive contact is observed between the clean sands and the overlying IHS, marked by the development of a granular lag with siderited clasts along the surface (Fig. 2.35). Additionally, discontinuities within the overlying IHS are present (Fig. 2.36).

INCISED VALLEY DEPOSITIONAL MODEL

A model is needed to explain how such stacked deposits accumulated with an organized relationship. Such a model must include aggradation of the system to explain the stacking, and also explain how the IHS sets may be stacked with consistent

Figure 2.35. Erosional contact between megaripple bedded sand and IHS (Lithosome D) in outcrop along the Athabasca River. **(A)** General view with granular sand at the base of the IHS succession sitting atop fine sand of the megarippled facies. **(B)** Close up of the contact showing a concentration of sideritized pebbles. Rare *Conichnus* are present in the megarippled sands. This is significant, as the group of anemones to which *Conichnus* are attributed are not tolerant of significantly reduced salinity. This implies that the megaripple bedded sand was deposited under near marine salinity. **(C)** Close up of the contact showing sizable sideritized clasts.

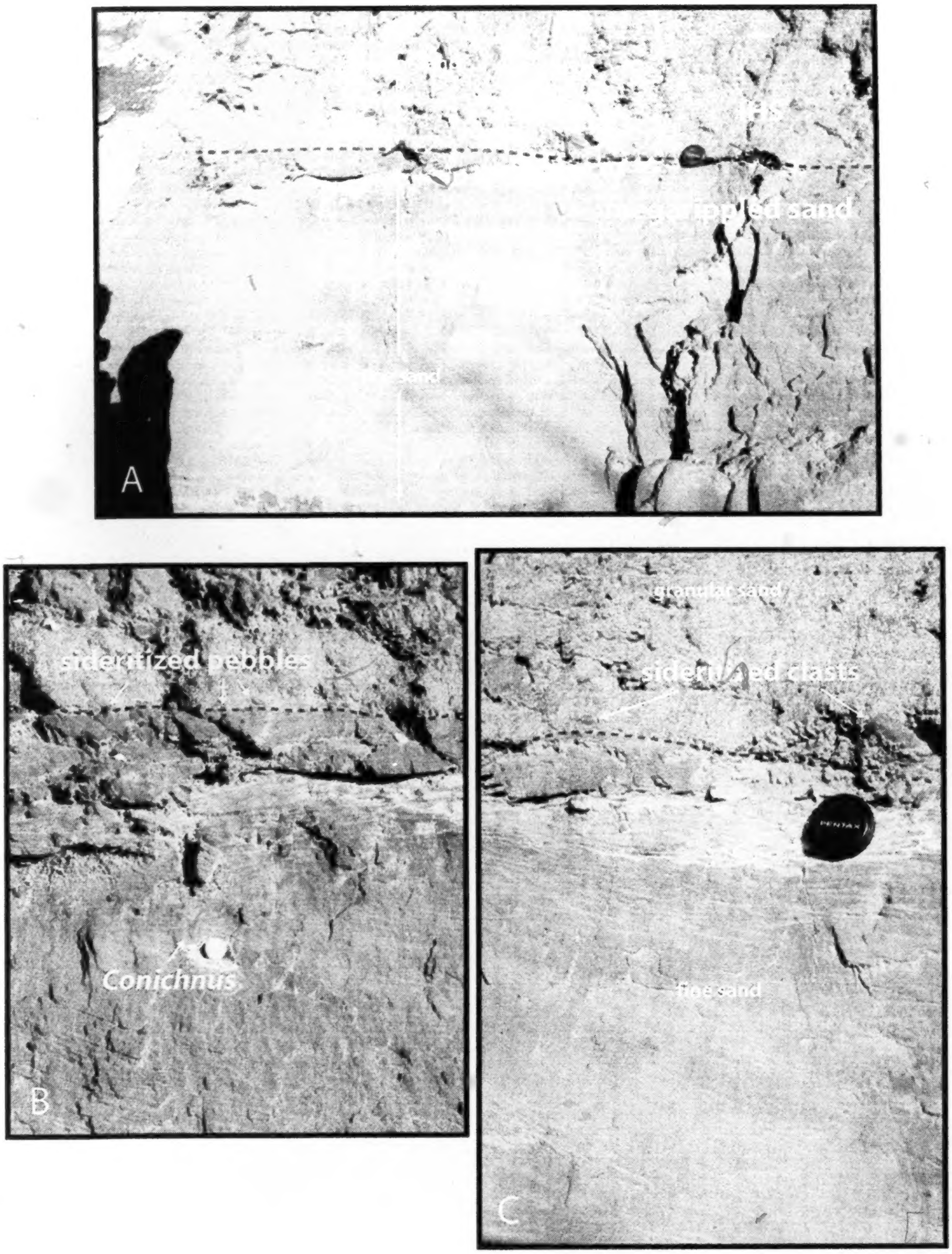

rippled sand
sand
A
sideritized pebbles
Conichnus
B
granular sand
sideritized clasts
fine sand
C

Figure 2.36. Discontinuities within a succession of IHS in outcrop along the Athabasca River. **(A)** While appearing superficially as a single set of IHS, this succession can be broken down into a series of stacked muddying upwards units. This outcrop face offers an oblique strike view. **(B)** A dip section view taken across the gulley from (A) reveals a stacking relationship between IHS units involving both vertical and lateral components, with clear angular discordance.

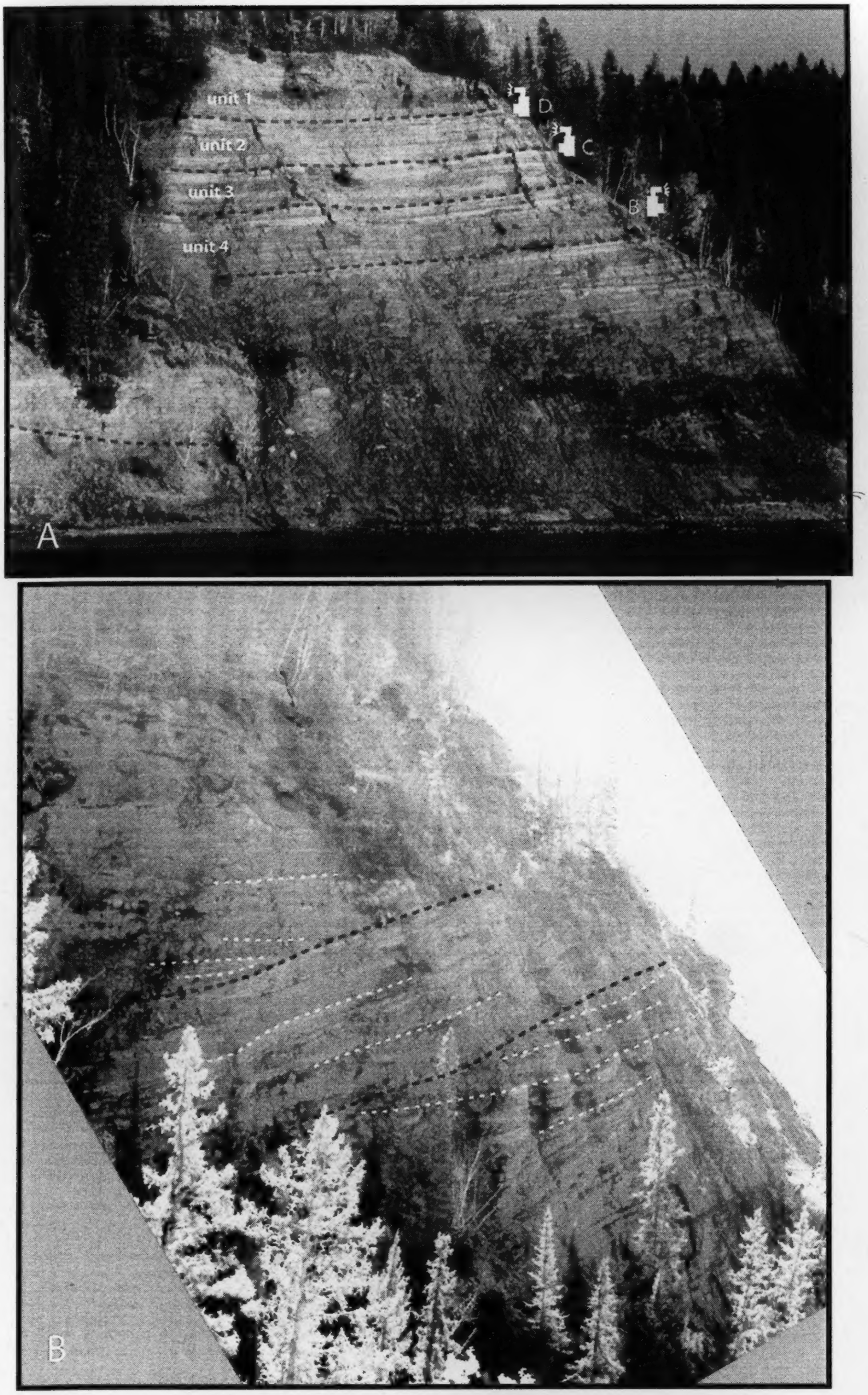
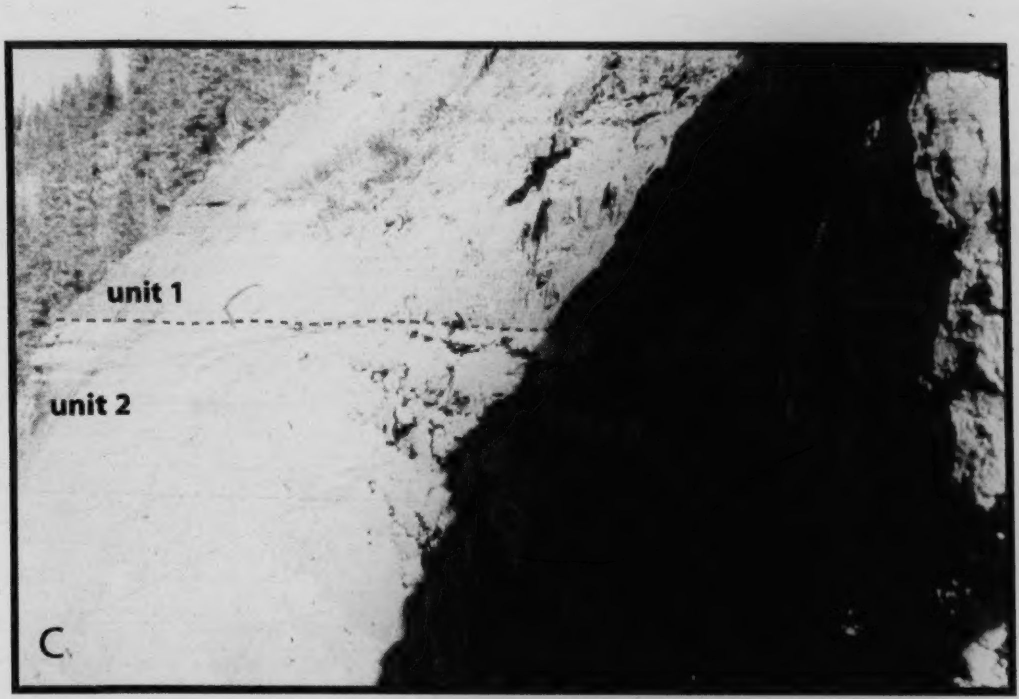
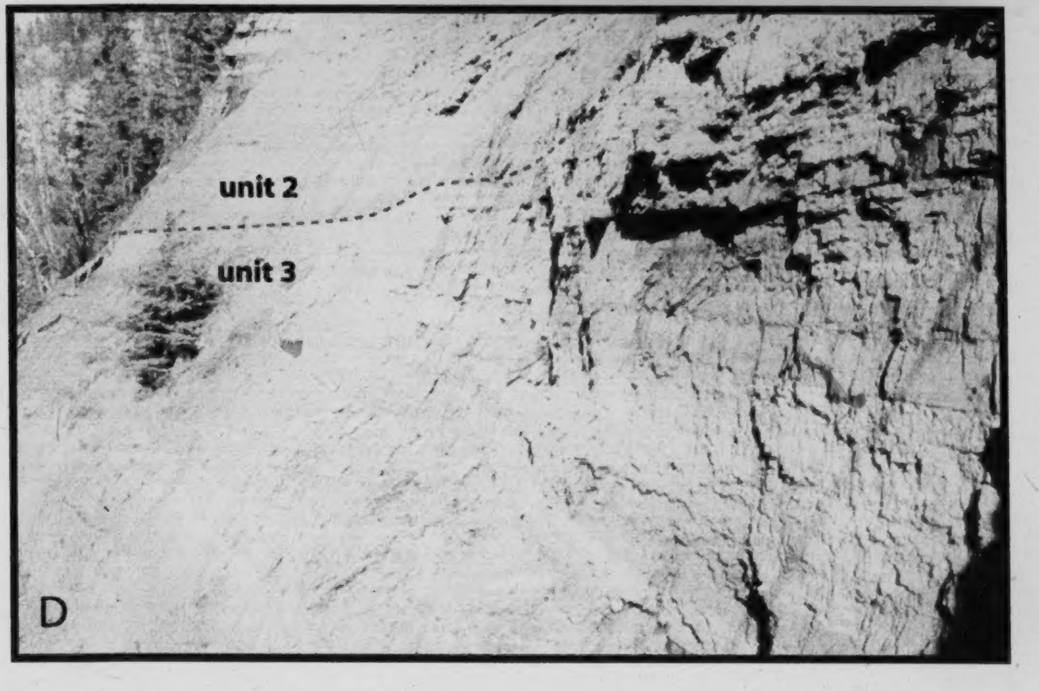

unit 1
unit 2
unit 3
unit 4
D
C
B
A
B

Figure 2.36 cont. Discontinuities within a succession of IHS in outcrop along the Athabasca River. **(C, D)** Outcrop views highlighting low angle truncation between upward muddying units outlined in (A).


unit 1
unit 2
C


unit 2
unit 3
D

orientation. An incised valley fill model may fulfill both of these requirements. While the repeated entrenchment and infill of valleys during McMurray Formation deposition has been proposed previously (e.g. Stewart and MacCallum, 1978; Ranger and Pemberton, 1997), it has not been used previously to explain the organized stacking of IHS sets.

The transgressive infill of a valley easily provides the required aggradation of the estuarine system, and may explain the locally observed relationship between the IHS and underlying trough cross-bedded sands as well. With initial transgression of the valley, a tidally driven outer estuarine sand wave complex may be established near the mouth of the valley, as the reduction of channel gradient leads to the large scale entrapment of fluvially sourced sediment further inland. When the system comes into adjustment with a marginal marine gradient, the channelized portion of the estuarine system progrades over the outer estuarine, sand wave deposits. This yields the relationship observed between the megarippled sand and IHS in several outcrops (Fig. 2.37). As the dynamics of transgression would vary from one episode of valley fill to another, the development of the megarippled sands would not have been universal, and would have taken place over a limited length of the valley.

As aggradation took place within the valley, some factor must have limited the migration of the tidal river to generate the stable dip orientation commonly seen within successions. One possibility is that combined lateral and vertical accretion of the channel in the outer, straight reaches led to the filling of the valley with a single IHS set significantly thicker than the causative channel (Fig. 2.38F). A second possibility involves the migration of the channel within a “narrow” confining valley. If the natural meandering amplitude of the channel exceeded the width of the valley in which is was found, the migration of the channel would be limited by the form of the valley. If the valley itself had a meandering form, the migration of the channel would be limited to movement from the inside to the outside of valley bends. Organized stacking of IHS sets may also have been influenced through the anisotropic erosional susceptibility of mud-bearing IHS.

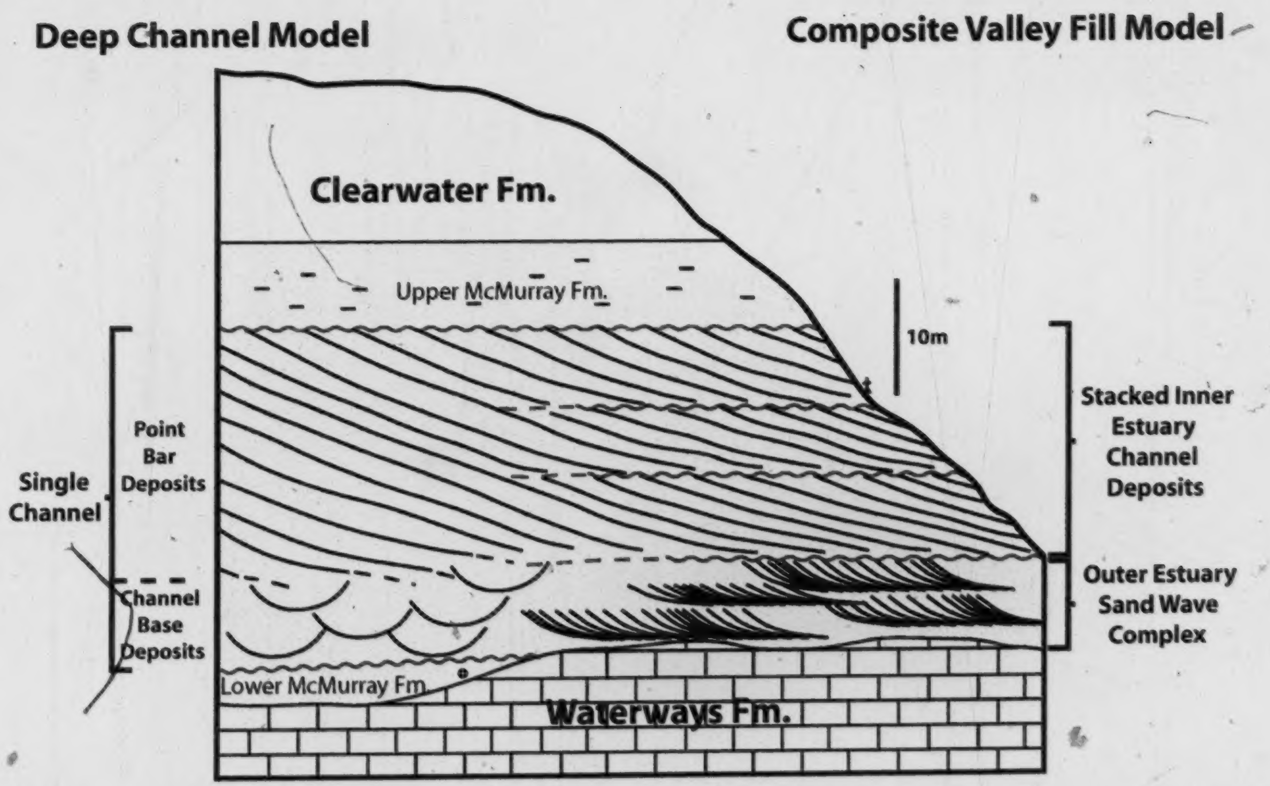
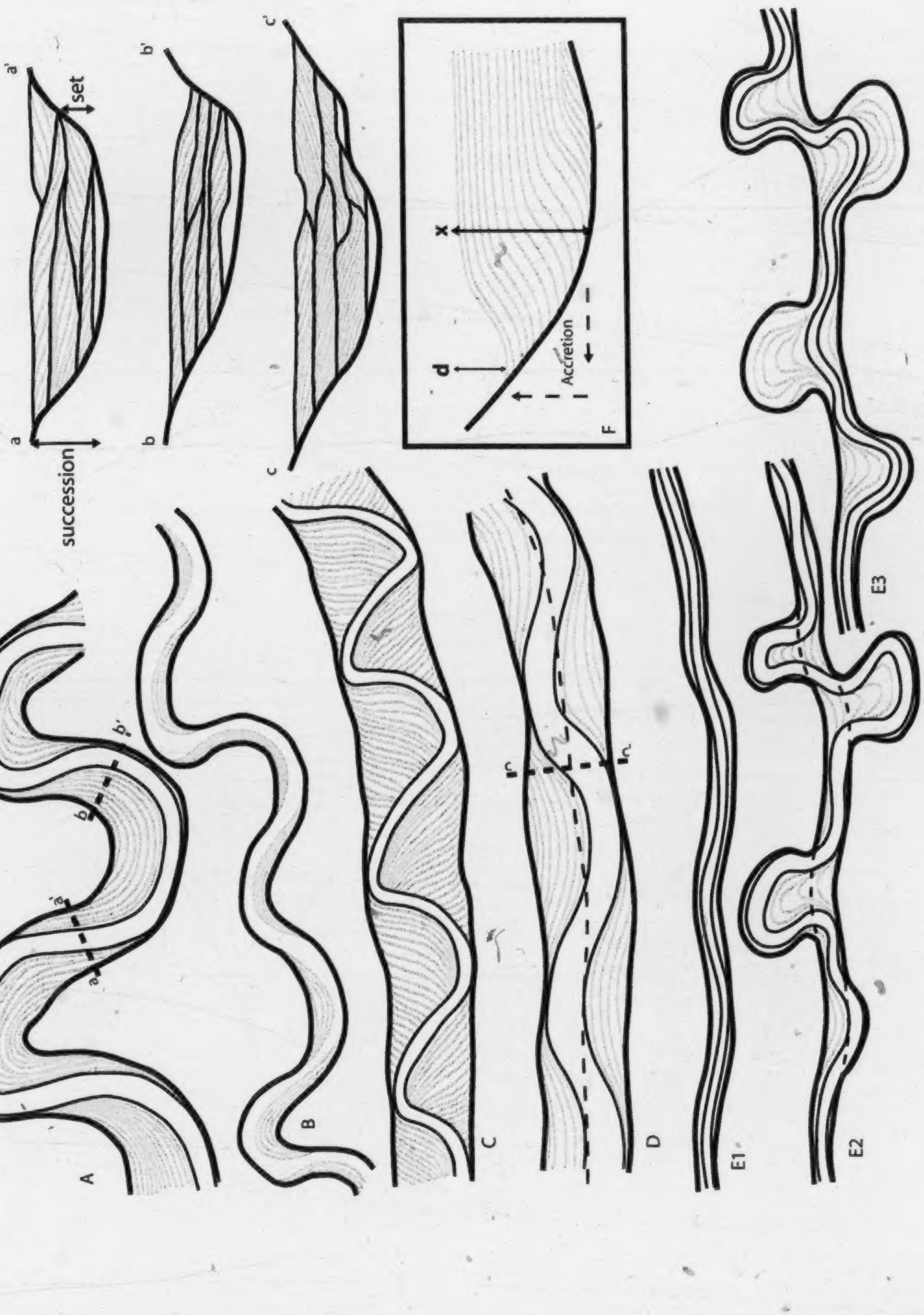


Figure 2.37. Comparison of the deep channel model and an incised valley fill model for middle McMurray IHS complex deposition. The deep channel model implies that the entire succession from the base of the megarippled sands to the top of the IHS (locally 40 m thick) was deposited by the action of a single, deep meandering channel. Megarippled sand deposition would have taken place at the base of the channel, while IHS was deposited on a contemporaneous point bar. The incised valley fill model implies that deposition of the succession took place in stages, as base level rose. The locally present megarippled sands would have been deposited in an outer estuarine sand wave complex after initial inundation of the valley. Subsequent progradation and aggradation of the estuarine system would lead to deposition of stacked channel deposits for the remainder of the valley fill. Modified after Mossop and Flach (1983).

Figure 2.38. Restriction of channel migration within an entrenched valley. **(A, B)** On bends in the valley, point bars build out only from the inside valley wall, thus limiting the orientation of IHS dips such that they are inclined to the outside of the bend. Near inflection points, IHS may be inclined to either side of the valley. **(C)** Where meanders migrate down valley, the orientation of IHS will be limited to an oblique inclination down valley. **(D)** Where the channel width is large relative to the valley width, point bars generally don't build out past the center of the valley, thus limiting the orientation of the IHS dips such that they are inclined to the center of the valley. **(E)** The formation and repeated occupation of discrete "meander pods". (E1) Fluvial bypass and valley entrenchment in semi-consolidated sediment. (E2) The onset of meandering leads to cutting of "meander pods". (E3) Valley form controls the locus and orientation of meanders through subsequent aggradational infill of the valley. **(F)** Through a smooth combination of lateral and vertical accretion, a continuous set of IHS can be generated which significantly exceeds the thickness of the causative channel. In this schematic, the set thickness as penetrated at point "x" exceeds the thickness of the causative channel, "d", by a factor of 2.5.


A
a
a'
b
b'
B
C
D
c
c'
E1
E2
E3
succession
set
a
a'
b
b'
c
c'
d
x
Accretion
F

CONCLUSIONS

IHS from the McMurray Formation displays substantial variability with respect to lithic and ichnologic character. The distribution and morphology of ichnofossils reflect systematic spatial and temporal variation in salinity and turbidity stress. By applying concepts gleaned through the study of modern estuarine systems, deposit character can be resolved into a fluvial to marine gradient. IHS character falls into a broadly tripartite distribution, with a sand-dominated seaward flux in the upper reach, a fine-grained zone of convergent flux in the middle reach, and sand-dominated landward flux in the lower reach. The sand dominated IHS deposits from each end of the system contrast strongly in terms of texture, structure, biogenic signature, and stratal organization. Similarly, fine members from the central portion of the system exhibit a progression of character from dense mud to finely interlaminated silt/sand and mud in a landward direction.

Not all occurrences of IHS within the McMurray Formation can be resolved into a fluvial to marine gradient, as many channels within the estuarine environment are not discretely linked to continental drainage. The situation is further complicated by the existence of numerous fluvial systems entering the marginal marine realm at different positions along the axis of the main system. Each of these continental drainage systems would have had differing provenance and discharge dynamics.

The dominant order of cyclicity within the IHS is annual, with subordinate semidiurnal and fortnightly tidal signature locally evident. The heterogeneity of the sediment character is influenced largely through seasonal variation in fluvial discharge, and the evolution of estuarine water circulation and sediment flux that results. Inter-annual variation in allocyclic forcing may have led to the inconsistent character of inclined units observed in IHS deposits from the ends of the channelized system.

Firm ground ichnofossil suites are developed internal to some variants of IHS, but do not carry with them any stratigraphic implication.

Successions of superficially consistent IHS can attain great thicknesses, but are typically broken by subtle discontinuities into several smaller depositional units. The megaripple bedded sands, which are often present at the base of such successions, are not directly related to, or co-depositional with, the IHS. These successions thus represent accumulations of loosely related, stacked depositional units, rather than the deposits of a single channel sweep. An incised valley fill model adequately explains the observed relationships.

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CHAPTER 3 – THE MORPHOLOGY AND PALEOENVIRONMENTAL SIGNIFICANCE OF *Spirascensus conferti*: A PREVIOUSLY UNDESCRIBED HELICAL ICHNOFOSSIL FROM THE LOWER CRETACEOUS OF WESTERN CANADA

INTRODUCTION

Within the Lower Cretaceous McMurray Formation of northeastern Alberta (Fig. 3.1), the accretionary bank deposits of tidally-influenced channels are very common. In 2002, a core-based study was initiated to catalogue and interpret the variation present within these deposits. Through this study, a unique facies was identified with a distinct, anomalous bioturbate texture. This facies consists of thin, mud-rich accretionary bank deposits with a monospecific, highly abundant, assemblage of minute, helical ichnofossils (Fig. 3.2). The diminutive size of the traces, combined with the presence of a pervasive bitumen stain, has made their characterization an involved process.

While no prior detailed examination of these traces has taken place, they have been previously encountered within the Cretaceous Mannville Group of western Canada (Bechtel, 1996; Hubbard, 1999). Within the McMurray Formation, Bechtel (1996) dealt briefly with this ichnofossil, treating it as a variant of *Gyrolithes*.

In an effort to characterize the bioturbate texture, its ethology and paleoenvironmental significance, burrowed intervals from eight well cores and a single outcrop were examined and sampled. Core face examination yielded information on the gross morphology and community behavior of the traces. Examination of thin-sectioned samples provided fine detail on the subtleties of the burrow form.

STRATIGAPHIC AND ENVIRONMENTAL SETTING

The Lower Cretaceous McMurray Formation hosts most of the bitumen present within the Athabasca Oil Sand Deposit, and as such plays a significant role in energy

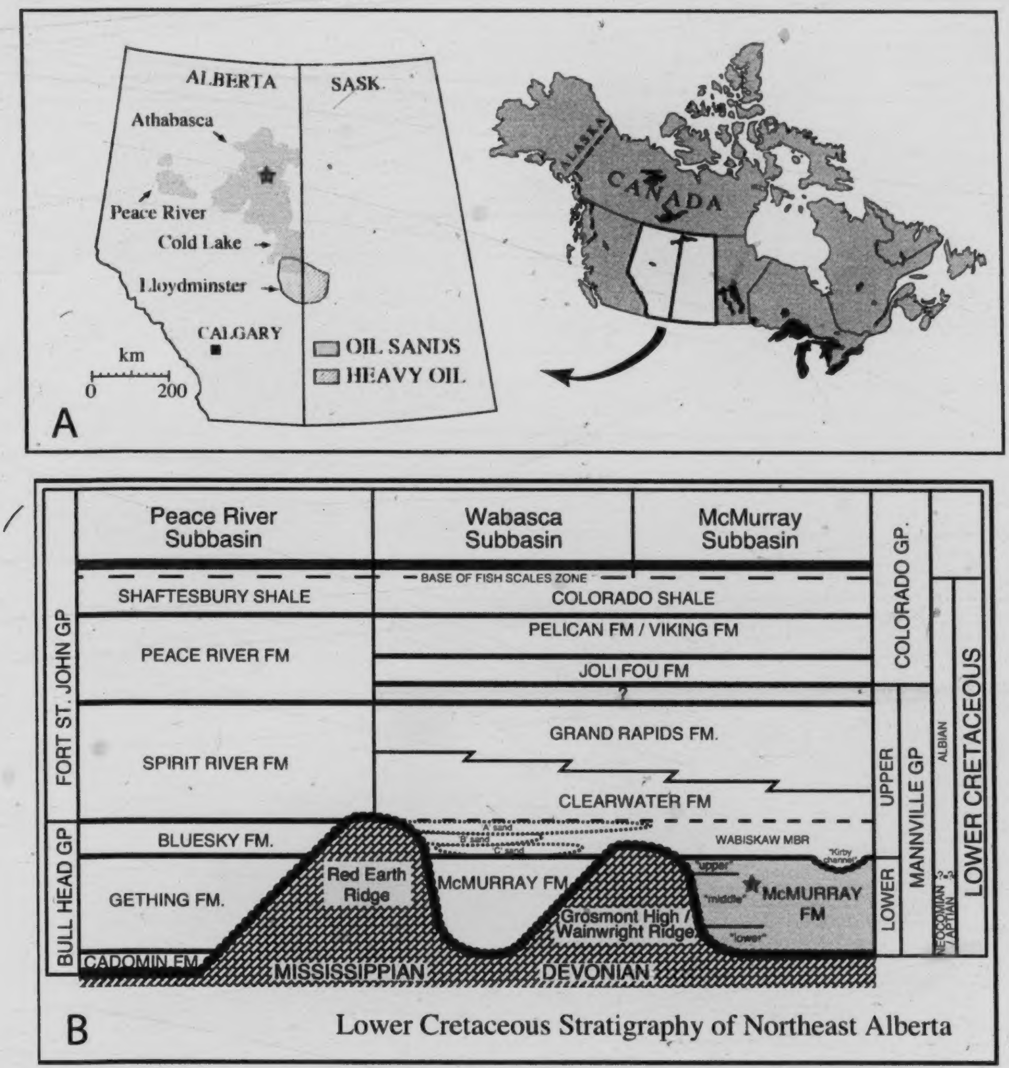


Figure 3.1. Geographic and stratigraphic situation of the examined burrowing. **(A)** Oil sand and heavy oil deposits of Alberta. Core and outcrop examined are from the Athabasca Oil Sand deposit. **(B)** Stratigraphy of Lower Cretaceous strata within northeast Alberta. Red star marks the approximate stratigraphic location of the examined channel bank deposits. From Ranger and Gingras (2003).

production within North America. The McMurray Formation consists of pulsed transgressive deposits lying unconformably on a Devonian carbonate terrane. Deposition was generally confined to a broad erosional trough cut through differential erosion of the tilted carbonate strata, and the solution removal of evaporitic horizons at depth. The McMurray Formation has been informally divided into lower, middle and upper members

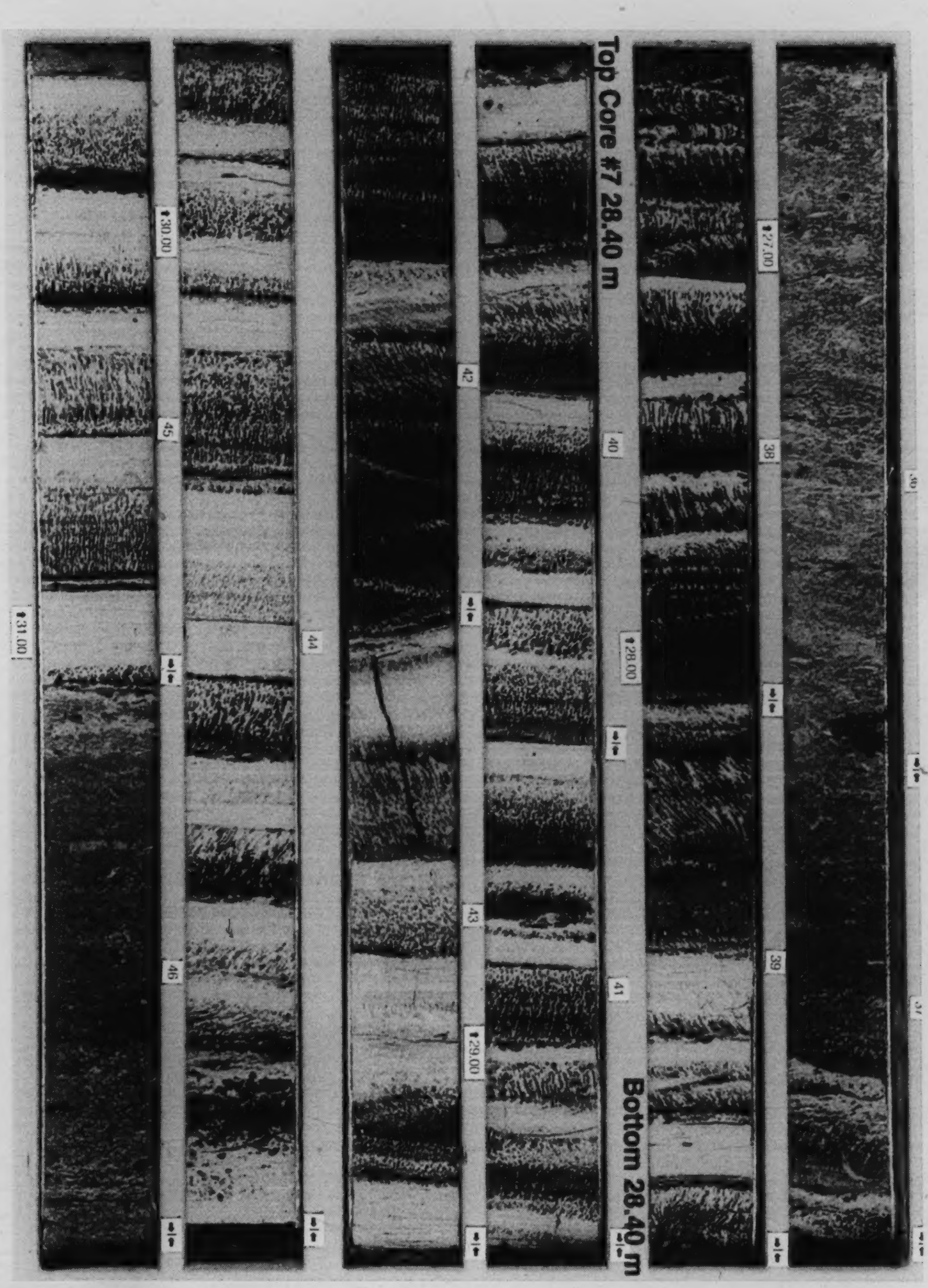


Figure 3.2. Channel bank accretion deposits pervasively burrowed by minute, helical ichnofossils. Bottom of core to the lower left, top to upper right, core in 75 cm lengths. Note the inconsistent development of the sediment couplets, and the persistence of the burrow assemblage through the interval. From AA/12-08-96-11 W4.

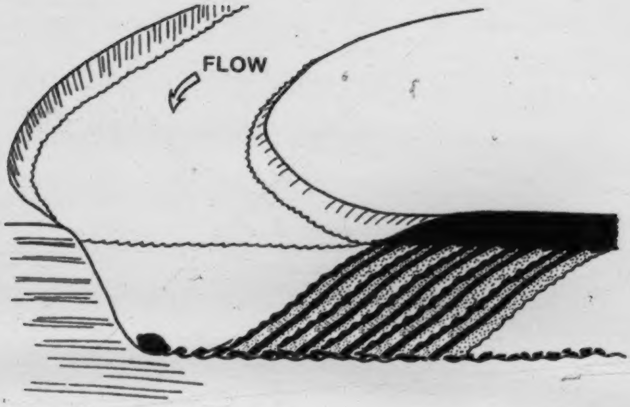


Figure 3.3. Generalized model for the accumulation of inclined heterolithic strata on the accretionary bank of a meandering channel.

(Carrigy, 1959), loosely reflecting continental, estuarine and shoreline depositional environments, respectively (Ranger and Gingras, 2003). These deposits are overlain by glauconitic shoreface sandstone and basinal mudstone of the Clearwater Formation.

Inclined heterolithic stratification deposits (IHS) (Thomas et al., 1987) - comprised of rhythmically alternating granular and muddy beds laid down with a significant depositional dip (Fig. 3.3) - form a major component of the estuarine middle McMurray Formation. Through ichnological investigation and comparative work undertaken in modern tidal rivers, the IHS packages have come to be interpreted as the accretionary bank deposits of estuarine channels (Pemberton et al., 1982; Smith, 1987). The dominant order of heterogeneity within the IHS is annual. Cyclic deposition is interpreted to have been generated through seasonal changes in the patterns of estuarine water circulation and sedimentation. Examples of seasonal change in the depositional character of partially mixed estuaries are well documented within modern settings (Allen et al., 1980; Uncles and Stephens, 1993; Lesourd et al., 2003).

The sedimentologic and ichnologic character of IHS packages vary considerably within the McMurray Formation. This diversity of character is attributed to both varying position along tidally influenced channels, and the presence of different channel types within the greater estuary. Each of the examples hosting the helical burrowing dealt with in this paper is composed of fining- and muddying-upward couplets of very fine sand, silt and clay. Individual couplets are typically 5 – 15 cm thick. Preserved set thicknesses reach 6 m, and dips vary between 2° and 14°, often with an upward-steepening profile. These features indicate that sedimentation took place under active channel migration. Were the IHS deposited within abandoned channels, one would expect a more homolithic fill with lower bedding inclination and an upward-shallowing dip profile (Muwais and Smith, 1990).

The stacking of two or more of these IHS sets is common, often with contrasting stratal orientation between them. The deposits themselves typically contain significant quantities of phytodetrital material and rooting and phytoturbation are occasionally preserved at the top of the sets (Fig. 3.4). Within the single outcrop example, the helically-burrowed IHS interval is overlain by a poorly developed coal. In several examples, these intervals are immediately underlain or overlain by coarse, wood clast-bearing sands of interpreted fluvial origin.

TAXONOMY

Ichnogenus *Spirascensus* gen. nov.

Synonymy

Gyrolithes var., Bechtel, 1996, pp. 29-33, figs. 9c, 12b; Hubbard, 1999, fig. 2.16c; Harris, 2003, fig. 2.16a,d; Ranger and Gingras, 2003, fig. 82.

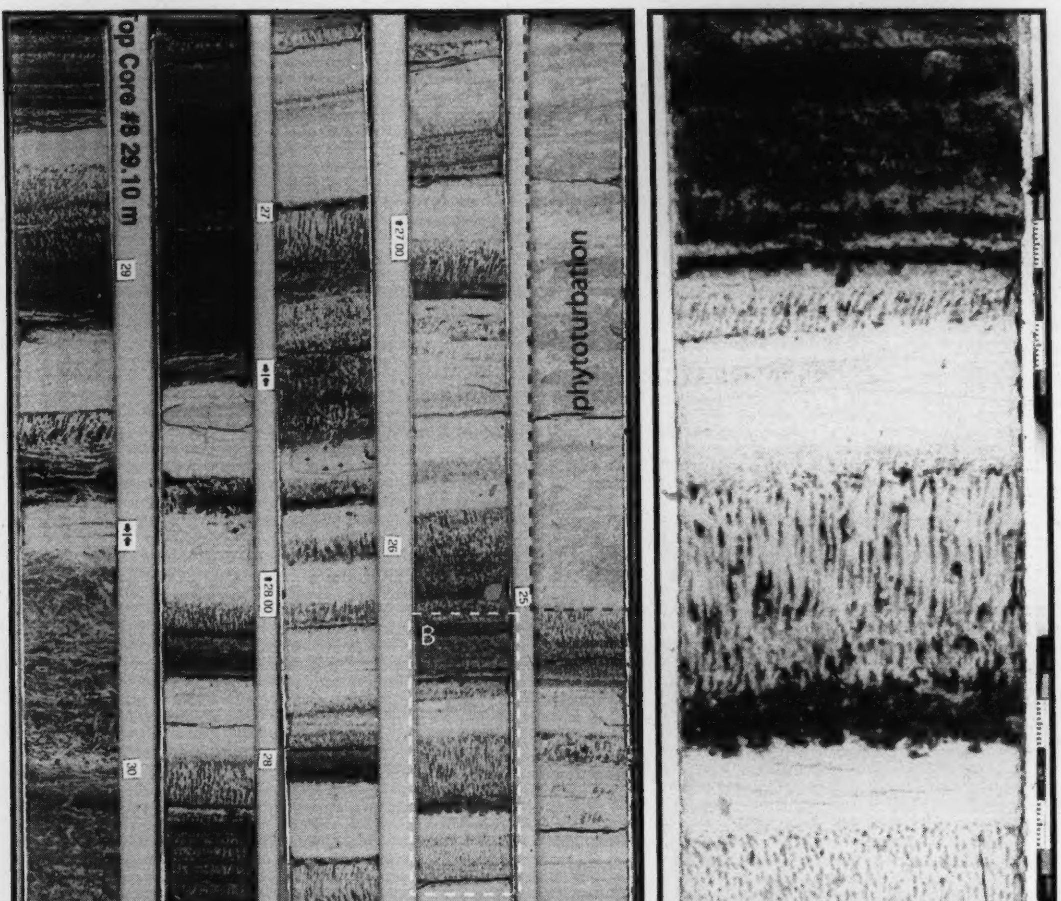
Etymology

spira (lat.)=coil; ascensus (lat.)=ascent.

Type ichnospecies

Spirascensus conferti sp. nov.

Figure 3.4. Rooting and phytoturbation at the top of an IHS set burrowed by *Spirascensus conferti*. **(A)** Overview showing the zone of phytoturbation, and the depth to which discrete roots penetrated. Bottom of core to lower left, top to upper right, core in 75 cm lengths. From AA/05-08-96-11 W4. **(B)** Close-up view showing discrete coalified roots and the pattern of bioturbation within several sediment couplets. **(C)** Close-up view illustrating fine aspects of the burrow morphology. Note the presence of a muddy spindle-like structure central to the granular fill of most burrows.


Top Core #8 29.10 m
29
30
Bottom 29.10 m
27
28.00
28
27.00
26
25
phytoturbation
A
B
C

Diagnosis

Dextrally of sinistrally coiled, elongate, vertical to inclined burrow with consistent width; fill is active and texturally distinct from host sediment; upward burrow migration may be evident.

Distinction from other ichnogenera

Spirascensus is distinguished from *Gyrolithes* by its active, sorted fill, elongate form and upward migration within rapidly aggraded sediments. *Spirascensus* lacks the central shaft and spreitenated structure of *Spirophyton*. While *Lapispira* is composed of two nested coils joined at the base, *Spirascensus* has the form of a single coil. *Helicorhaphe* is a horizontally oriented sole trace. *Helicolithus* and *Helicodromites* are horizontally oriented, meandering graphoglyptids.

Spirascensus conferti sp. nov.

Etymology

confertum (lat.)=shoulder to shoulder

Holotype

Figure 4, AA/05-08-96-11W4, 26.0 – 29.5m depth in core.

Type Locality

Fort McMurray, Alberta, Canada.

Type Substrate

Inclined Heterolithic Strata of the informally designated middle member, McMurray Formation.

Diagnosis

Burrow process less than 1 mm in diameter, whorl diameter less than 3 mm; within heterolithic sediment, burrow fill texture varies inversely with host sediment texture; enriched mud core central to coil and muddy fecal trail central to burrow process may be present with granular burrow fill.

OCCURRENCE

MORPHOLOGY OF THE TRACES

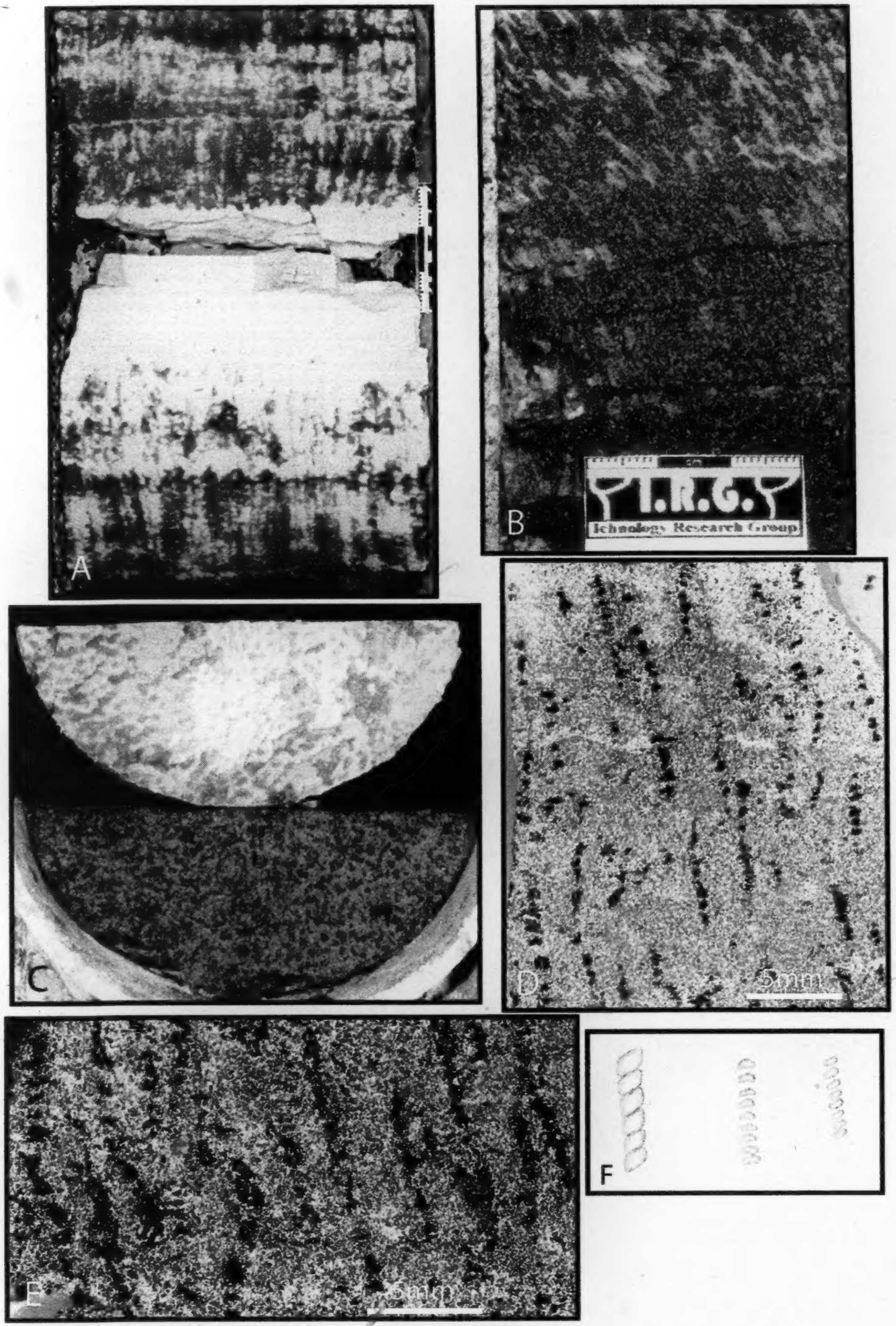
The textural contrast between host substrate and *Spirascensus conferti* burrow fill is variably developed as discrete muddy burrow fill in silt/sand and discrete silt/sand fill in mud. Additionally, subvertically banded silt/sand and mud with no clear distinction between host and burrow fill material is seen as a transitional phase. Henceforth, clay-poor granular sediment is referred to as sand, and clay-rich sediment is referred to as mud. Burrow character varies systematically through each sediment couplet, reflecting the variation in host sediment texture. The typical succession consists of muddy burrow fill in sandy host sediment towards the base of the couplet, passing through a transitional phase into sandy burrow fill in muddy host sediment towards the top. Many couplets contain only part of this succession, owing to subdued variation in sediment texture. The burrows are present in organized communities, nearly always oriented vertically, or normal to sediment stratification. Individual burrows have typical whorl diameters of <1 to 2 mm. They are distributed with roughly consistent lateral spacing and generally do not intersect. Although individual burrows can rarely be traced for more than 2 to 3 cm due to oblique intersection in core face, consistent burrow communities 10 to 15 cm in vertical thickness are commonly seen. Burrowing is seen to exhibit significant discontinuity of character at the contacts between sediment couplets.

Within sandy host sediment, the longitudinal expression of the burrows is highlighted by discrete muddy structures in the form of stacked platelets or a tight coil (*sensu* twisted rope) (Fig. 3.5). In the stacked platelet variant the mud is concentrated into separate packets arranged in a discontinuous column. The tight coil variant, however, is composed of a single, continuous muddy structure. In transverse section, the burrows appear as circles or ellipses of mud in the sandy host. When viewed in thin section, the burrow fill is seen to consist of clay and fine silt, contrasting significantly with the host sand, which often reaches upper very fine in grain size.

Where *Spirascensus conferti* is expressed as a sand fill within a muddy host substrate, more complex and varied structure is observed (Fig. 3.6). In longitudinal section, burrows may be expressed simply as a granular column with undulating margins, but mud-defined internal structure is commonly present. In many examples, a thin central spire of mud (occasionally enriched in organic debris) extends the length of the sandy column. This spire may be of consistent width, or show undulatory variation. Where such a central spire is present, the surrounding granular fill occasionally exhibits clear grain alignment, arranged concentrically in circular pods on either side of the spire, or occasionally radiating outwards with a subhorizontal fabric. Thin drapes of mud connecting the central spire to the outside wall of the burrow between the granular burrow process are locally observed. In some cases where fine detail is preserved, a thin mud-enriched trail is seen to follow along the center of the coiling burrow process. This may represent a fecal string extruded into the burrow, as seen with *Phycosiphon* .

Corresponding variation is also seen in transverse sections of the sand filled burrow segments. Some burrows appear as simple sand filled circles in a mud host. In others, the sand is present as a ring or arc around a muddy core (the central spire). In a few burrows, spreiten are observed within the burrow fill, implying lateral migration or sediment packing. Where the sediment contains significant quantities of coarse organic detritus (silt to fine sand in size), this material is commonly enriched in the sandy burrow fill relative to the muddy host sediment. The sandy fill of these burrow segments is often

Figure 3.5. Mud filled *S. conferti* within sandy host sediment. **(A, B)** Longitudinal expression in core face. Note that the burrow fill may occur as a continuous structure, or as a column of discrete mud packets. **(C)** Transverse expression along bed partings. Width of core is 6.5 cm. Above are sand filled burrows within a mud host sediment, below mud filled burrows in sand. Note the high density and even areal distribution of the burrows. **(D, E)** Thin sectioned samples. Note the discontinuous nature of many burrow fills, and the contrast in grain size between the host sediment and the granular component of the burrow fill. **(F)** Schematic illustrating the variable expression of mud filled burrows.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C
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E
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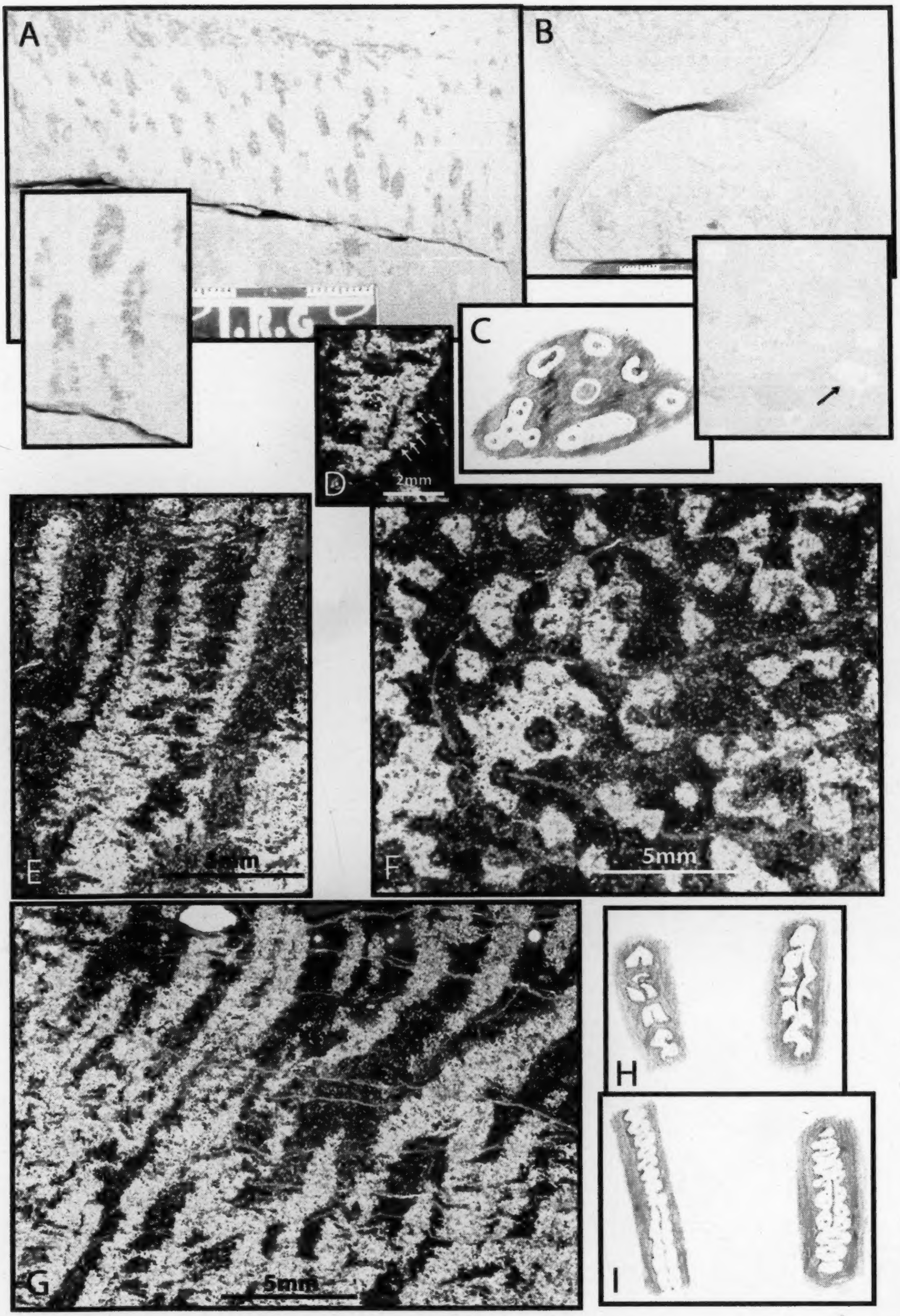
Figure 3.6. Sand filled *S. conferti* within muddy host sediment. **(A)** Oblique longitudinal expression in core face. Note the presence of muddy spindle-like structure central to many burrows, and discrete intersections of the burrow process and core face (inset). **(B)** Transverse expression along bed partings. Burrows are typically expressed as a ring of sand around a muddy central core. Some burrows exhibit a spreitenated structure (inset), suggestive of lateral migration, or sand packing around the burrow. **(C)** Schematic illustrating variable expression of sand filled burrows in transverse section. **(D)** Oblique longitudinal thin section of burrow. Note the repeated intersection of a discrete burrow process with a thin mud trail central to it (solid arrows). Also present is a vertical mud spire central to the coil of the burrow (dashed arrow). **(E)** Longitudinal thin section of burrowing. While not as pronounced as in (D), a coiled burrow process with a central mud trail is discernable. **(F)** Transverse thin section of burrowing. Note the inconsistent expression of the central mud spire, and the clustering of some burrows. **(G)** Longitudinal thin section of burrowing. Note the presence of a thin mud spire in some burrows, and the local deviation of the parallel burrow fabric. **(H)** Schematic illustrating examples of clear burrow morphology observed in core face. **(I)** Schematic illustrating examples of clear burrow morphology observed in thin section.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notably coarser than the granular fraction of the muddy host sediment. This implies that the trace maker was redistributing sediment in a vertical sense rather than simply filling its burrow with "cleaned" host sediment.

Where the sediment is transitional in character between sandy and muddy end members, burrows commonly appear as a muddy fill within a sandy sheath, itself surrounded by apparently undisturbed mud (Fig. 3.7). This variant is seen to interfinger vertically with mud filled and sand filled burrow character.

The traces exhibit both dextral and sinistral coiling. While the burrows are typically oriented subvertically in stable substrates, substantial shearing of the burrow fabric is not uncommon, owing to compaction and shearing effects within many of the muddier horizons (Fig. 3.8). The traces are also seen to deflect where they encounter cross-stratified sand, maintaining a roughly surface-normal orientation. The downward deflection of sediment interfaces within the burrow fill is locally apparent, indicating that the trace makers migrated upwards with active sedimentation.

ORGANIZED COMMUNAL STRUCTURE

One of the most striking aspects of these burrowed deposits is the strict regularity with which the IHS couplets have been colonized. Almost invariably, each sediment couplet has been colonized through the entire vertical extent of the genetic set. In the rare instances where other ichnotaxa are present, however, the population of *Spirascensus conferti* is significantly reduced. This may reflect very low competitive ability, a predatory relationship or a short-lived change in environmental parameters.

A clear link is observed between the cycle of sedimentation and the dynamics of the trace maker community. In addition to the gradual change in burrow expression within each sediment couplet, and the sharp character change at the contacts between couplets, the density and size of traces are also seen to vary. While some variation takes place within the couplets themselves, changes are most evident at the contacts between

Figure 3.7. Transitional expression of *S. conferti*. **(A, B)** Longitudinal expression in core face. While the sediment has a clear bioturbate fabric, it is difficult to discern between host and burrow fill material. **(C)** Schematic illustrating the juxtaposition of muddy host sediment, muddy burrow fill within a sandy sheath, and sandy burrow fill. **(D, E)** Longitudinal expression in thin section. Again, note the juxtaposition of stacked mud packets and sand filled burrows with muddy central spires, illustrating the transition between end member burrow character.

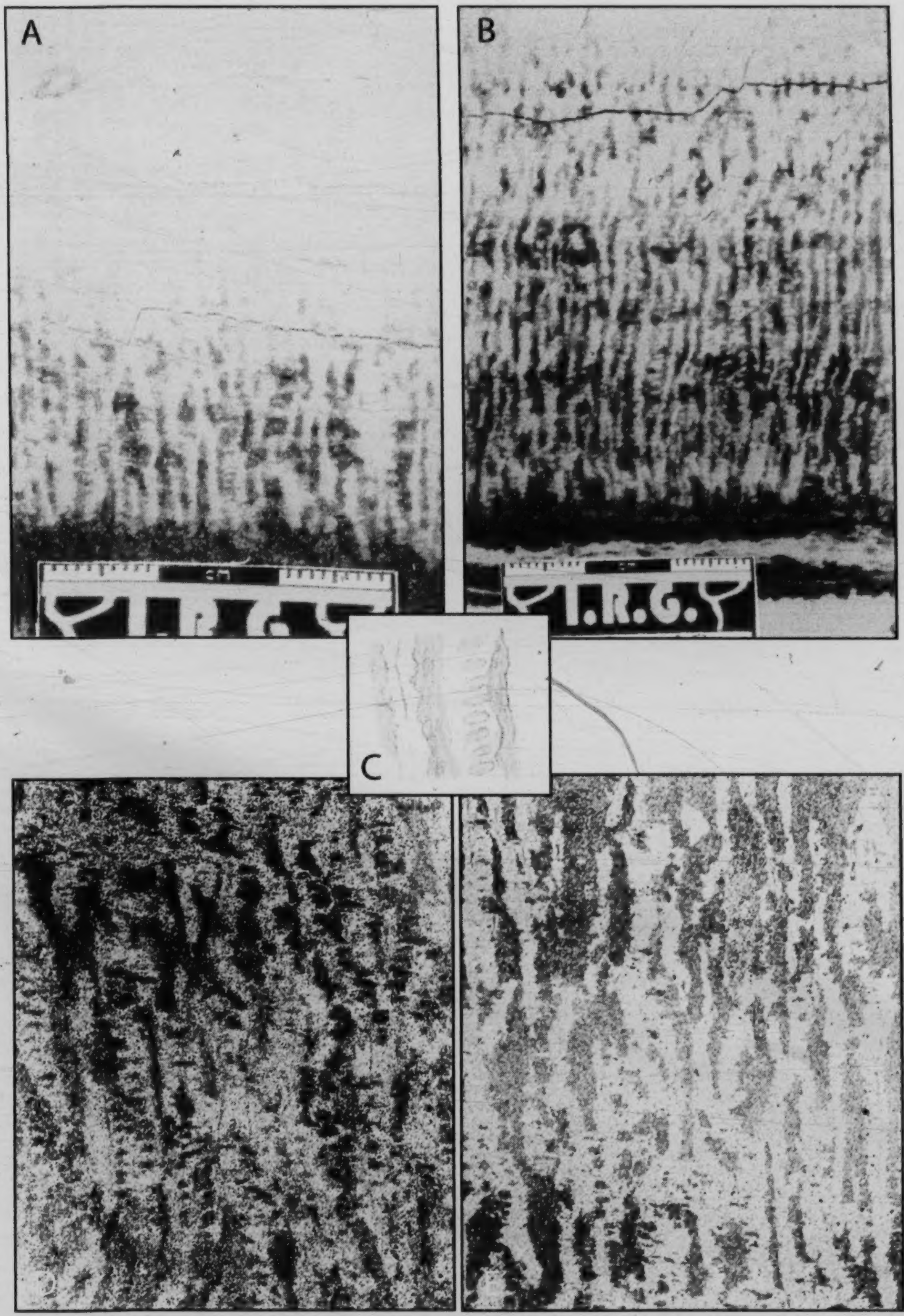
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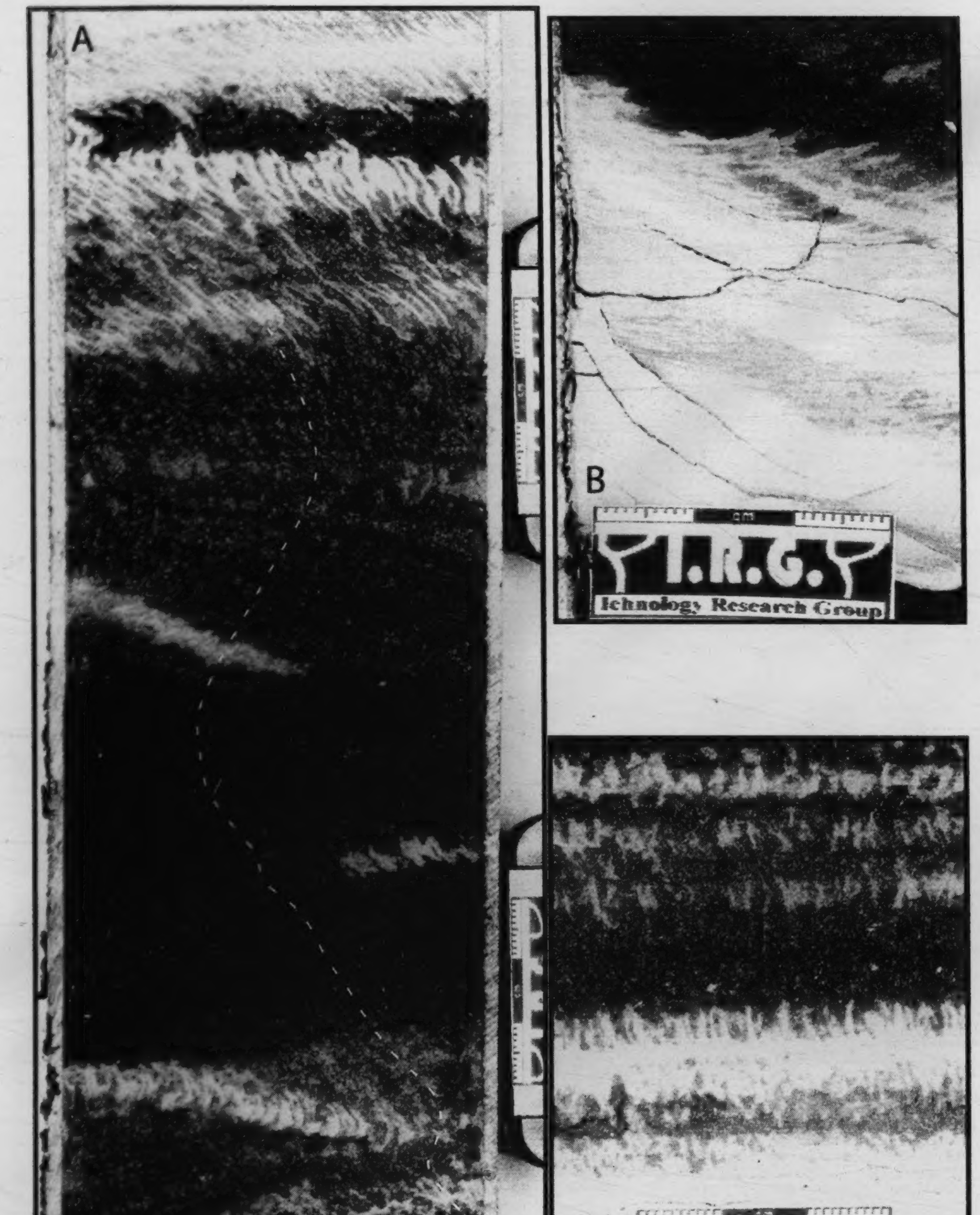
Figure 3.8. Characteristics of burrow fabric. **(A)** Deflection of burrow fabric through cross-stratified sediment. The broken white line tracks burrow orientation. **(B)** Deformation of burrow fabric through compaction and shearing of muddy sediment. **(C)** Downward deflection of sediment interfaces within burrow fill. Sediment interfaces have been deflected approximately 5 mm (coiled length of juvenile trace makers?) within the burrow fill, implying the upward migration of the trace makers with sediment accumulation.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couplets. Many of these sedimentary contacts are associated with a clear decrease in the size, and increase in the abundance of individual traces (Fig. 3.9). In one example, this change reflects a greater than two-fold increase in population, with a corresponding decrease in burrow width. In many other instances, a gradual decrease in the abundance of traces is seen through the muddy upper portion of a sediment couplet, followed by the reestablishment of populous burrowing within the sandy base of the superjacent couplet.

Population density often approaches the physical limit at which adjacent burrows would interfere with each other. A sampling of burrow density along bedding-normal sections yields typical values of 50 000 – 200 000/ m^2. Where population density is low, the axes of the traces often deviate from the parallel, surface normal pattern observed with dense populations.

DISCUSSION

BEHAVIOR OF THE TRACE MAKERS

Helical burrow morphology

Many factors may have played a role in influencing the helical form of the burrows. The possibilities reflect both behavior inherent to the producing organism, and adaptive response to their environment.

With larger helical burrows, such as *Gyrolithes* and *Daimonelix*, the functional morphology of the trace maker's skeleton has been proposed as a possible impetus for the arcuate shape. With occurrences of *Gyrolithes*, inequality in the cheliped size of burrowing decapods has been suggested, with the preference for the use of one cheliped over the other in excavation (Farrow, 1971). This forces the burrow to deviate from a straight form. Similarly, the preference of a burrowing beaver to cock its head to one side while excavating with strokes of its incisors may be behind the curvature of *Daimonelix* (Martin, 1994). *Spirascensus conferti*, however, was most likely created by a soft-bodied

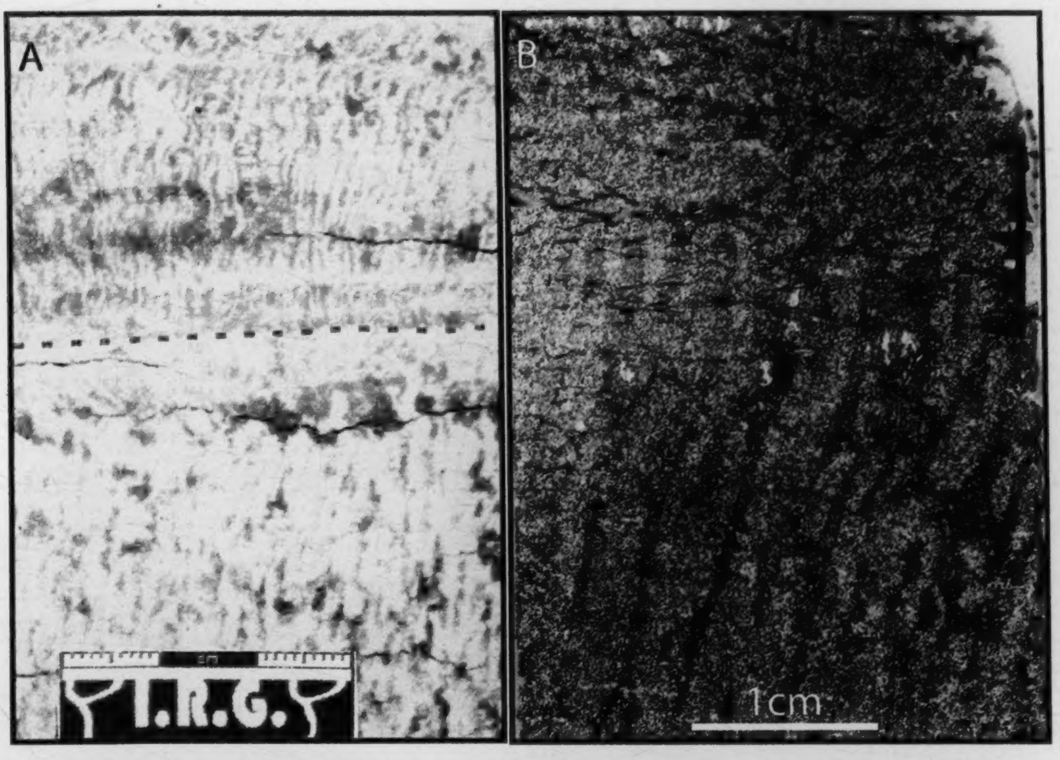

Figure 3.9. Interface between successive generations of burrowing. **(A)** Core face expression associated with a dramatic decrease in the size of the traces, and a 2.2x increase in their density. **(B)** Thin sectioned example. Location different than (A). While such interfaces are typically seen in association with the succession of muddy sediment by sandy sediment of the subsequent sediment couplet, they are most clearly observed where they occur within the muddy sediment.

worm, and thus would not have been influenced by skeletal morphology.

A helical burrow may have been a behavioral adaptation intended to aid in buffering the burrowing organism from salinity fluctuation in the overlying water column. With such morphology, the trace maker increases the effective contact between its body and the surrounding sediment, maximizing the buffering effect afforded by the comparatively stable sediment pore water. The coiled shape may also prove more difficult to flush through the hydrodynamic action of the water overlying the sediment.

The length of body and burrow that can be fit into a given thickness of sediment is maximized through a coiled habit. This may be of great importance if a limited geochemical window were available for colonization. In coiling, the burrower can maximize its gut and body length to promote efficient digestion and absorption of nutrients across the body wall. With a helical form, the volume of sediment accessible from a single vertical penetration of the sediment is increased without necessitating an increase in the size of the burrow process itself.

Increased grip on the sediment may be another advantage of a coiled burrow. This would impact the organism's ability to migrate within the burrow and resist extraction under the influence of strong current and predation. The coiled morphology may also improve the burrower's ability to force itself into unburrowed sediment, and manipulate the sediment surrounding its body through constriction and expansion. This may be an effect means by which burrow diameter is expanded to accommodate the introduction of an active fill or lining.

If the migration of pore water through the burrow is taken to be an important process, the coiled form may have implications on the nature of the flow in sand filled burrow segments. The helical form would increase the interaction between the flowing water and the host sediment by maximizing the volume of sand through which water flows, and increasing the surface area of muddy host sediment exposed to the water.

Separation of the sediment into granular and muddy fractions

In both mud dominated and sand dominated substrates, burrowing has fractionated the sediment into discrete muddy and granular domains. Grain size selectivity in feeding may have contributed to this situation through the separation of an ingested and subsequently extruded mud fraction, and a rejected sand fraction. This process does not, however, explain the grain size distributions observed in thin section. With selective feeding alone, one would expect to see the sand filled burrow segments filled with a "cleaned" equivalent of the host sediment. As noted earlier, however, the sand fill is often notably coarser than the granular component of the hosting mud. The trace maker nay have been acting to promote the flow of pore water through the creation of discrete, permeability pathways. The sediment couplets, as laid down physically, would have had very low permeability normal to the bedding, owing to the presence of continuous, dense muddy layers. Through burrowing, the sediment has been transformed into network of permeable pathways cutting through the mud beds and dramatically increasing the potential for cross-stratal flow.

The process responsible for this enhanced fractionation of the sediment is somewhat unclear, although it seems apparent that some vertical transport of sand took place. Two possible actions may have been responsible for the vertical transport. The burrower may have transported coarser sand up from the base of the couplet into the muddier upper level. Alternately, it may have actively passed coarse material down into its burrow from the sediment water interface, and allowing finer material to accumulate as the "host" sediment.

Interpreting the presence of the muddy central spire in some variants of the sand filled burrows is somewhat problematic. This feature appears to reflect actively emplaced material, rather than relic host sediment. Central spires typically contain much less granular material than the muddy host sediment, and some are clearly enriched in organic matter. Their presence in some burrows may reflect fecal stowage behavior, an attempt to influence the flow of pore water, or both.

Carbonaceous debris has clearly been subject to preferential incorporation within the burrow fill. This likely reflects preferential feeding on small organic particles (explaining enrichment within muddy burrow fill) and microbes growing on and around larger particles (explaining enrichment within sandy burrow fill). The incorporation of carbonaceous debris may also reflect a gardening behavior, promoting the growth of microbes within the burrow subsequent to the initial sediment processing.

Given the variability in burrow character between sandy and muddy fill, it is likely that the differing expressions of individual *Spirascensus conferti* burrows would be discriminated as separate ichnotaxa if not encountered in such an obviously intergradational relationship.

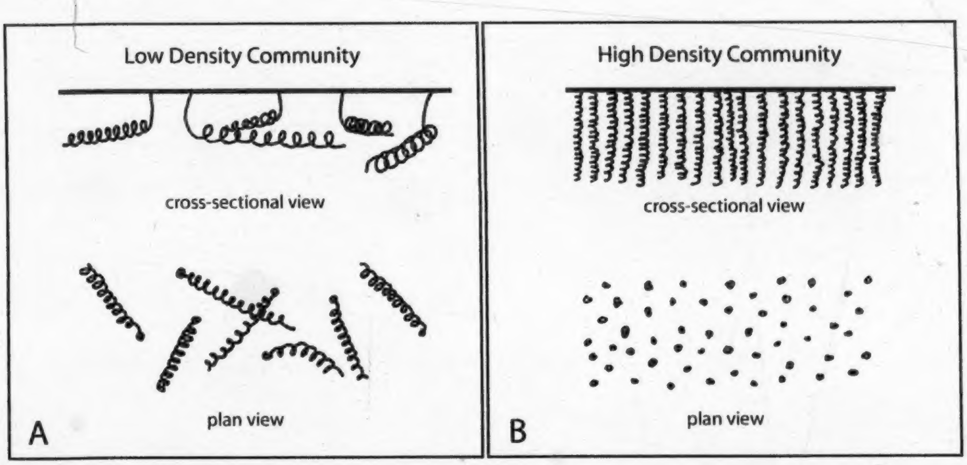

Figure 3.10. Effect of population density on burrow fabric. **(A)** In low density communities, the burrows have a substantial horizontal component to their form. Burrows show no organized relationship, and exhibit random avoidance. The horizontal component of the burrows may be focused on nutrient-rich horizons. **(B)** In high density communities, the burrows display a surface-normal parallel relationship. This organized community structure allows for high population density with minimum interference between individuals.

Community behavior

The exceptional population densities seen, coupled with the stable and repeated nature of colonization allude to a very rich and stable food source. The absolute dominance of *Spirascensus conferti* suggests a niche environment which was exploited exclusively by a single burrowing organism.

The organized, parallel, surface-normal relationship exhibited by individual traces within the burrow suite indicates a stable, territorial relationship between individual trace makers. Where the trace makers had sufficient real estate, they display a tendency to flatten with depth, perhaps exploiting particularly nutrient-rich horizons. Under the influence of crowding, however, they orient their burrows normal to the sediment-water interface, a response that allows for maximum population density and minimal interference between neighboring trace makers. (Fig. 3.10). This change in community structure between high and low population densities indicates that the organized, parallel relationship between individuals was a response to a population stress, rather than an inherent behavioral trait of the burrowing organism. Miron et al. (1991) noted a similar tendency for the polychaete *Nereis virens* to alter its burrow form from U-shaped to I-, L-, or Y-shaped under the influence of high population density.

The increase in density and decrease in size of the traces across discrete horizons is interpreted to reflect the succession of a mature population of burrowers with a fresh juvenile population. The fact that these repopulation events are typically found at the contact between couplets, combined with the evidence for upward migration, indicate that the life dynamics of the burrowers were intricately tied to the cycle of sediment accumulation. A new population was established with the onset of each annual depositional cycle, and burrow aggradation took place to keep pace with sedimentation. The gradual upward increase in size and decrease in density of the traces within a sediment couplet is taken to reflect maturation and attrition of the trace maker community.

COMPARISON WITH OTHER HELICAL ICHNOFOSSILS

The comparison of *S. conferti* to other helical ichnofossils serves both to support its taxonomic distinction, and illustrate the unique behavior it reflects.

In the past *S. conferti* has been interpreted as a variant of *Gyrolithes* (Bechtel, 1996; Hubbard, 1999). Known occurrences of *Spirascensus conferti* contrasts significantly with published examples of *Gyrolithes* in the scale of the traces. *S. conferti* typically exhibits a burrow process less than 1 mm in diameter, and a whorl diameter of <1 – 2 mm, while *Gyrolithes* commonly has a shaft diameter of 5 – 10 mm and a whorl diameter of several cm (e.g. Gernant, 1972; Bromley and Frey, 1974; Wilson, 1985). Even with diminutive variants of *Gyrolithes* encountered in brackish strata of the Mannville Group, whorl diameters typically approach 1 cm (Beynon et al., 1988; Bechtel, 1996). While *S. conferti* reflects the active redistribution of sediment by an upward migrating deposit feeding, or gardening organism, *Gyrolithes* is generated through the passive infill of a domicile excavated down from the sediment surface. *Gyrolithes* is commonly found in an intergradational relationship with horizontal trace forms (typically *Thalassinoides*), however, no such relationship is seen with *S. conferti*.

Spirophyton is another spiral-form trace known to occur in brackish environments (Miller and Johnson, 1982; Miller, 1991; Ranger, personal communication). The typical size of *Spirophyton* (whorl diameters of 2 – 5 cm) is, however, out of agreement with that seen in *S. conferti*. Additionally, *Spirophyton*'s morphology, with a spreitenated structure spiraling around a vertical axial tunnel, differs from *S. conferti*, which takes the form of a simple coil. As with *Gyrolithes*, *Spirophyton* is created through downward burrowing from the sediment water interface (Miller, 1991).

Lapispira consists of two nested helices joined at the base, and is commonly more than an order of magnitude larger than *S. conferti* (Lange, 1932).

Helicodromites, *Helicolithus* and *Helicorhaphe* are all lengthy, horizontally oriented helical or screw shaped traces expressed in semirelief along cleavage surfaces. They are interpreted to reflect the grazing of mobile deposit feeders. Examples of *Helicodromites* are larger than *Spirascensus conferti*, with a 2 mm thick process and approximately 2 whorls per centimeter of length, while *Helicolithus* and *Helicorhaphe* are known to be comparable to *S. conferti* in tunnel and coil diameter (approximately 1 mm and 3 mm respectively). *Helicolithus* and *Helicodromites* are graphoglyptid forms, exhibiting a regular meandering course. *Helicorhaphe*, on the other hand, exhibits a nearly straight course. *Spirascensus conferti* differs fundamentally from *Helicodromites*, *Helicolithus* and *Helicorhaphe* in its stationary habit, and vertical orientation.

INTEGRATED TROPHIC MODEL

By bringing together elements from the depositional environment, morphology and interpreted behavior of *Spirascensus conferti*, a trophic model can be generated to explain the maintenance of such a dense community (Fig. 3.11). The presence of a vegetated supratidal overbank brings two key elements to the model: a source of

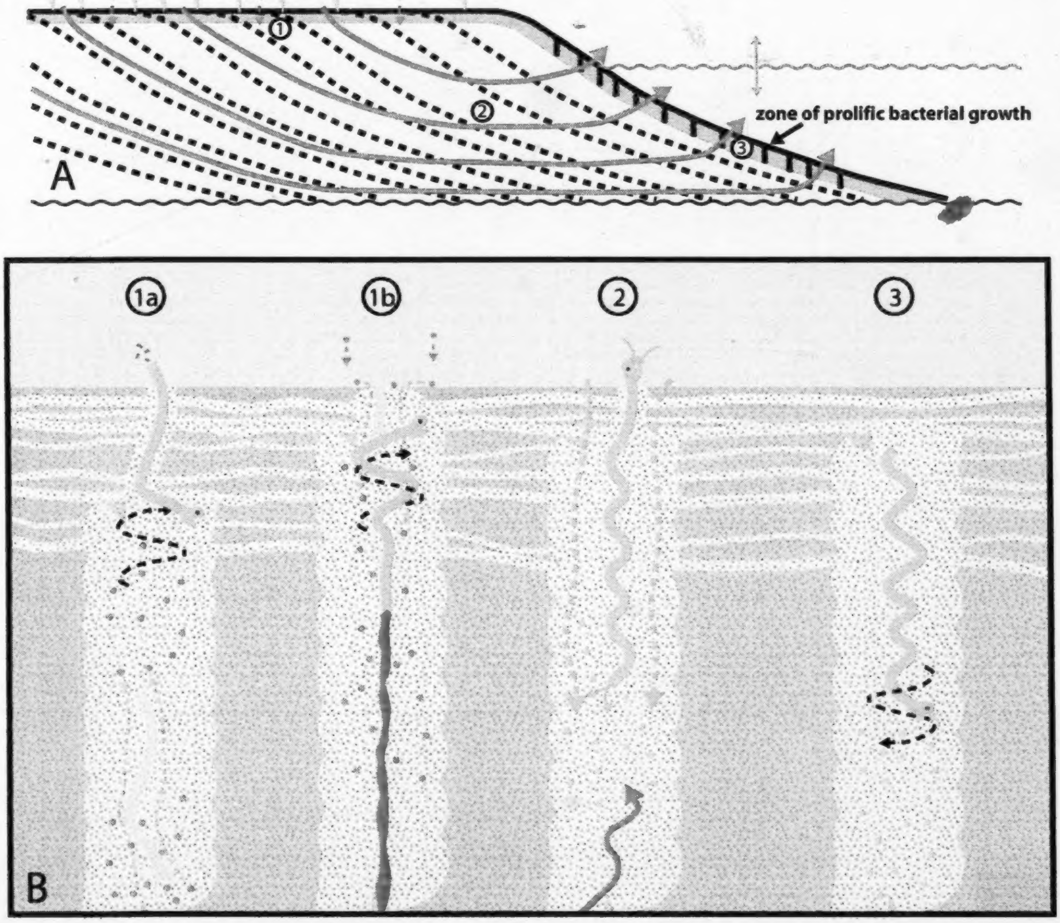

Figure 3.11. Integrated trophic model explaining the maintenance of a high density infaunal community within channel bank sediments. **(A)** Productive pore water flow architecture within the bank. (A1) Water laden with dissolved organic material (DOM) infiltrates the top of the bank. Available oxygen is quickly consumed through the oxidation of a fraction of the DOM. (A2) A hydraulic gradient set up within the channel drives pore water towards the active channel bank. Flow is facilitated through the permiability enhancement of historic *Spirascensus conferti* burrowing. (A3) Within the surficial layer of the bank sediment, the mingling of DOM-rich pore water and oxygen-rich channel water promotes the growth of bacterial. **(B)** Burrowing and feeding stages of the *S. conferti* trace maker. (B1) Fractionation of sediment, and processing of fines. The trace makers may be situated with a heads-down arrangement (a) passing fecal material into the water column, and transporting coarse sand for burrow fill up from depth. Alternately, they may be situated with a heads-up arrangement (b) concentrating fecal material into a central mud spire and passing coarse sand for burrow fill down from the surface. (B2) Gardening of bacteria and absorption of DOM. Pore water rich in DOM and oxygen-rich channel water are mingled through tidal pumping and/or active irrigation by the trace makers, promoting the growth of bacteria. At this stage, the trace makers may be feeding through the direct absorption of DOM. (B3) Cropping of bacteria. The trace makers reprocess the sediment, feeding on bacteria and their secretions.

degradable organic matter, and a mechanism through which pore water flow may be induced. As water is introduced to the top of the bank - either through precipitation or extreme high tides - it infiltrates into the bank carrying with it soluble organic compounds from decaying plant matter. After infiltration, this water rich in dissolved organic matter (DOM), quickly reaches a reduced state through the oxidation of organics. Aided by enhanced permeability generated through *S. conferti* burrowing, and a hydraulic gradient within the bank, the water flows towards the channel. As it approaches the sediment-water interface at the channel margin, the DOM-rich water is mingled with oxygen-rich channel water through tidal pumping, and possibly active irrigation by the *S. conferti* trace makers. Within the zone of mixing, biotic activity is promoted by the presence of both the degradable DOM and oxygen.

In this model the trace makers active at the point bar surface have access to three food sources: organic detritus deposited with the sediment, DOM introduced through pore water flow, and bacteria feeding on the organic detritus and DOM. The balance between these three sources may vary during the course of a sediment/population cycle due to changing textural character of the accumulating sediment and variation in precipitation (and thus infiltration and pore water flux).

On a fine scale, the action of the burrowing organisms themselves plays a major role in the maintenance of this system, through the generation of permeability pathways across the stratal fabric of the sediment, and the promotion of bacterial growth.

This model is supported by two pieces of circumstantial evidence. First, the extreme population and sessile character of traces are inconsistent with a community supported solely through deposit feeding. A scheme leading to the localized availability of food would seem to fit much better. Secondly, lithologically comparable IHS deposits interpreted to have been deposited in areas with subtidal and intertidal overbank (thus no significant plant growth or pore water flow) exhibit a fundamentally different ichnological signature, dominated by comparatively robust *Planolites* and *Teichichnus*.

ANALOGOUS MODERN BURROWING AND POSSIBLE TRACE MAKERS

While no modern burrowing directly analogous to *Spirascensus conferti* is known, several benthic organisms exhibit aspects of behavior similar to *S. conferti*, and may adopt a similar life habit under proper conditions.

It has long been speculated that *Gyrolithes* was produced by the burrowing action of decapods (e.g. Gernant, 1972; Bromley and Frey, 1974), but a clear modern analogue was not known until the work of Dworschak and Rodrigues (1997) on the burrowing shrimp *Axianassa australis*. While this has proven irrefutably that some decapods do construct regularly coiled burrows, their size and character are in agreement with *Gyrolithes* rather than *Spirascensus*.

The entrepneust *Saccoglossus* constructs a burrow on the order of 5-10 cm long, the lower portion of which often forms a regular spiral (Horst, 1940; Ruppert and Fox, 1988). Additionally, it is known to colonize the banks of tidal creeks in estuarine environments (Gingras et al, 1999). It is not, however, known to act as a deposit feeder.

Capitellid polychaetes are well known as motile, burrowing deposit-feeders (Fauchald and Jumars, 1979). Three well studied species, *Notomastus lobatus*, *N. latericeus*, *and Heteromastus filiformis*, construct burrows which are partially or completely coiled (Reineck et al., 1967; Powell, 1977; Gingras et al., 1999).

Notomastus lobatus makes vertically oriented, coiled burrows (Powell, 1977), while the coiled segment of *N. latericeus* burrows tend to be situated subhorizontally, either at the base of a U-shaped burrow, or extending between pirated burrows (Reineck et al., 1967). The size (with a burrow process on the order of 8 mm thick, and whorls 2-4 cm in diameter) and lack of active fill within the burrows of *Notomastus* render it a poor candidate for constructing *Spirascensus*-like burrows.

The "threadworm" *Heteromastus filiformis* inhabits the banks of intertidal creeks in estuarine settings. It constructs a branched, deeply penetrating burrow network with subhorizontal, helical terminations (Gingras et al., 1999). The worm itself typically reaches a length of 15 cm and a diameter of approximately 1 mm. *H. filiformis* densities of greater than 5000/ m^2 are not uncommon (Shaffer, 1983). It is a head-down deposit feeder that is well adapted to feeding within deep sulphidic sediments, a setting in which it faces little competition (Neira and Höpner, 1994). It is able to exploit this niche by maintaining contact with the sediment surface, where abundant oxygen is available, and actively irrigating its burrow (Fauchild and Jumar, 1979). Selective feeding by *H. filiformis* has been demonstrated, with its fecal material enriched over the host sediment in organic content and sediment of silt or finer particle size (Neira and Höpner, 1993). This, coupled with its head-down, surface-defecation habit leads to a vertical transport of sediment, and biogenic sorting. Neira and Höpner (1994) suggested the activity of *H. filiformis* promotes the growth of bacteria within the sediment, increasing its harvestable nutritive value, and that dissolved organic matter within the pore water may also contribute significantly to its nutritional budget. In a study of the population ecology of *H. filiformis*, Shaffer (1983) found that a discrete spawning event takes place annually. While he observed temporal overlap of the juvenile and adult populations, post-spawning mortality occurs with other polychaetes. Given an unstable, seasonal environment, it seems likely that post-spawning mortality could be induced in *H. filiformis* as well. *Heteromastus filiformis*, or a similar "threadworm" polychaete, would be an ideal candidate for making *Spirascensus conferti*-like burrows under the proper environmental influence.

CONCLUSIONS

Spirascensus conferti exhibits a complex morphology, with its expression varying in concert with changes in sediment character. Its morphology reflects a complex burrowing behavior involving the discrete segregation of muddy and granular fractions of the sediment, apparently to promote the movement of sediment pore water.

The traces are present in organized, parallel communities, interpreted to have arisen as a result of population stress. The life cycle of the trace makers was tied to the sedimentation cycle of the hosting sediment, with discrete repopulation events taking place on an annual basis. Colonization was very stable on an interannual basis, with the burrowing of each successive sediment couplet through the vertical extent of most examined IHS packages. This reflects a stable niche environment exploited by a single burrowing organism, to the exclusion of all others. While the extreme population, diminutive size and niche exploitation of the trace makers are characteristic of an opportunistic life strategy, the high productivity and stability of the hosting environment led to the establishment of a burrowing community that was very stable on an interannual basis.

The trace makers used a unique combination of sedimentological, ecological and hydrogeological conditions to support extreme population density. A beneficial pore water flow architecture - promoted through the burrowing activity of the trace makers themselves - led to a flux of nutrients through the body of the channel bank deposit and into the surficial sediment. This greatly increased the productivity and carrying capacity of the environment.

IHS deposits pervasively burrowed with *Spirascensus conferti* comprise a facies believed to be unique to actively migrating, low energy, tidally-influenced channels with a vegetated overbank. The common association of these deposits with coarse, fluvial sands suggest a depositional setting near the limit of tidal influence, where the alternation between small fluvial and tidal channel systems would be common. This facies therefore carries significant utility in the paleoenvironmental reconstruction of tidally-influenced marginal marine settings.

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CHAPTER 4 - CONCLUSIONS

Inclined heterolithic strata (IHS) deposits from the McMurray Formation display a substantial range of lithic and ichnologic character. This character is classified in a much more refined way than the classic "sand-dominated" versus "mud-dominated" scheme affords. The distribution and structure of ichnofossils within many IHS occurrences reflect systematic spatial and temporal variation in salinity and turbidity stress. Using a spatio-temporal framework based on the study of modern estuarine systems, deposit character is resolved into a fluvial to marine gradient along a riverine estuary channel.

IHS character falls into a broadly tripartite distribution, with a sand dominated seaward flux in the upper reach, a fine-grained zone of convergent flux in the middle reach, and sand-dominated landward flux in the lower reach. The sand dominated IHS deposits from each end of the system contrast strongly in terms of texture, structure, biogenic signature, and stratal organization. Similarly, fine members from the central portion of the system exhibit a progression of character from dense mud to finely interlaminated sand and mud in a landward direction.

A one-dimensional spatial model for IHS character along a tidal river provides a vector suitable for incorporation in paleogeographic reconstruction of channelized subsystems within the McMurray Formation. This permits more targeted exploration for high grade bitumen deposits, and may aid in the generation of a stratigraphic framework.

The dominant order of cyclicity reflected within the IHS was annual, driven through seasonal change in the dynamics of estuarine water circulation and sedimentation. The effects of semidiurnal, fortnightly and inter-annual cyclicity are locally apparent, but they were of subordinate importance in generating the heterolithic character of the deposits.

Although this model is a powerful tool, its application is not universal within the McMurray Formation. The model characterizes the deposits of the dominant tidal river channel, but the depositional character of modestly sized tributary systems may exhibit significant deviation from it. Complication is introduced through the influence the dominant system would exert over the dynamics of water circulation and sediment availability in tributary systems. The existence of three distinct provenances that drained into the McMurray Subbasin also adds variability. Systems entering from each of these continental districts would have contrasted in character of introduced sediment, and the dynamics of water influx. Additionally, some IHS-producing environments within the greater estuarine system did not connect to fluvial sources, and thus were not directly influenced by continental drainage.

Thick successions of IHS with broadly consistent character and stratal organization (locally exceeding 40 m) are present within the McMurray Formation. However, few, if any, of these successions are attributable to the migration of a single deep channel. The stacking of thinner genetic units (typically 5 – 15 m thick), many with consistent character between them, is by far the norm.

While megaripple bedded sands are present at the base of IHS successions in several prominent outcrops, the two lithic units were not co-generational. The megarippled sands exhibit several characteristics of higher energy, more marine deposition, and are commonly erosively truncated by the overlying IHS.

An incised valley fill model for the deposition of the IHS provides for a tidy relationship with the inconsistently developed megarippled sands. Such a model may also aid substantially in explaining the deposition of stacked IHS sets exhibiting consistent orientation.

IHS exhibiting an organized fabric of diminutive, helical ichnofossils forms a very distinctive facies within the McMurray Formation. The combined evidence of plant growth on a supratidal bank, the inferred behavior of the trace makers, and the high density of colonization, point to a uniquely structured deposit feeding and/or gardening community. This facies reflects a narrow environmental window, and as such may find utility in the construction of a paleoenvironmental or stratigraphic framework for the McMurray Formation and equivalent strata.